CONQUESTS OF ENGINEERING

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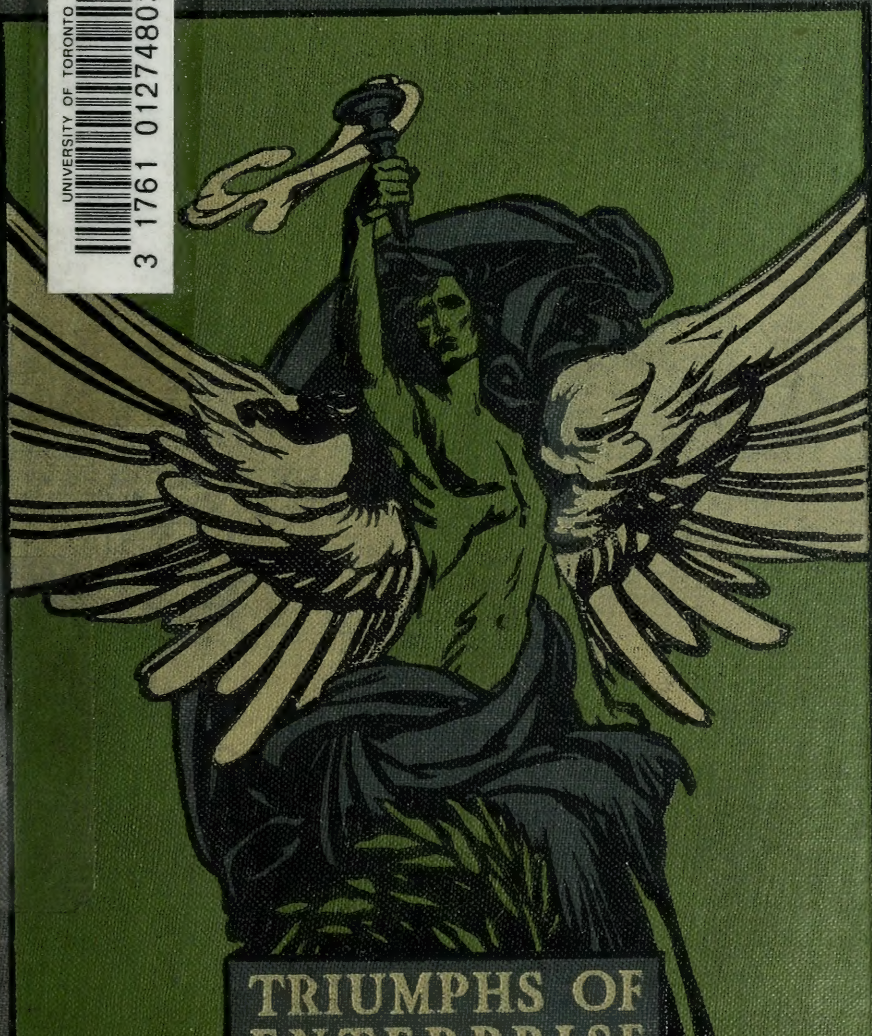

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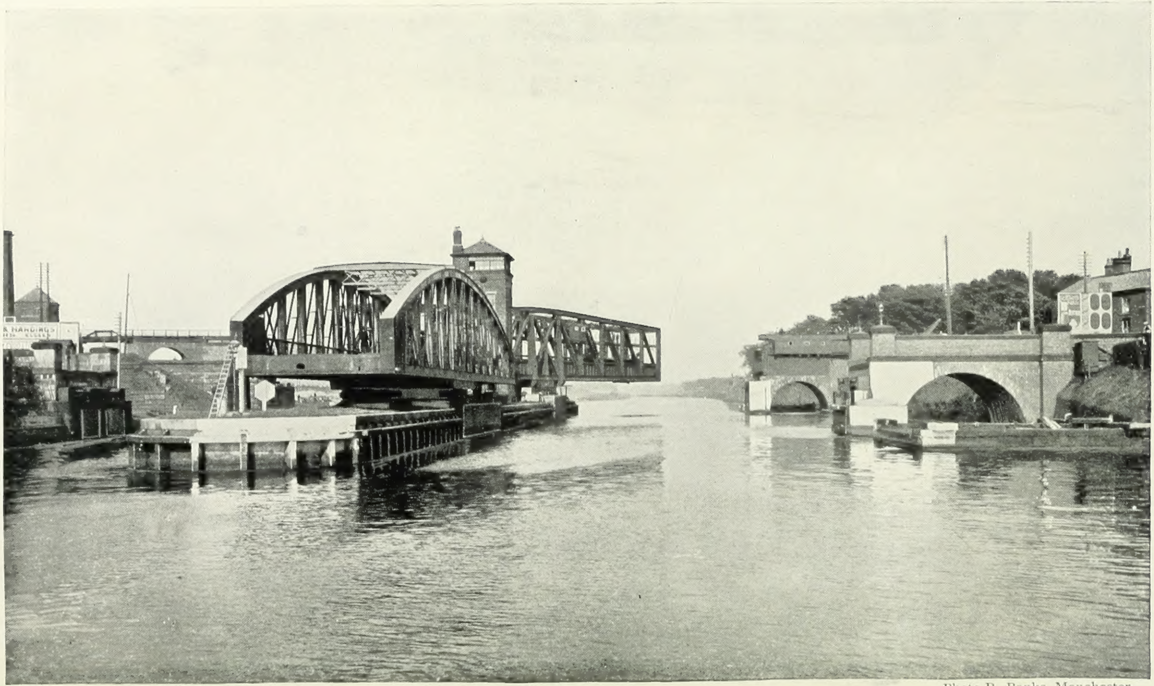

Photo R. Banks, Manchester

THE MANCHESTER SHIP CANAL

Barton Road Swing Bridge and the Barton Swing Aqueduct, the latter carrying the famous Bridgewater Canal over the Ship Canal

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Hal.

Conquests of Engineering

BY

CYRIL HALL

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Prefatory Note

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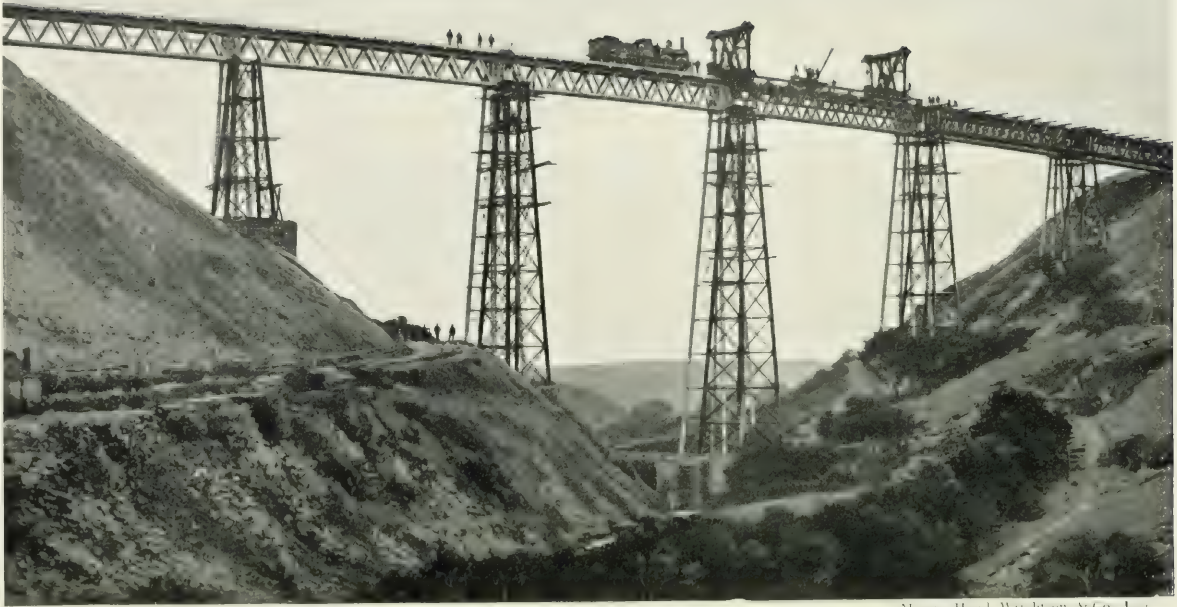

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MELDON VIADUCT, DEVONSHIRE

A graceful type of lattice girder bridge The "travellers" to the right of the locomotive are lifting a girder into position

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CONQUESTS OF ENGINEERING

CHAPTER I

The Art of the Bridge Builder

CONQUESTS of engineering! How many of us guess, as our train whirls us across the viaduct, or through the tunnel under the river, what great conquests these are, and what a great debt of gratitude we owe to those who designed and to those who built the works that enable us so easily to laugh at the gaps placed by Nature in our path? And how many of us realize that it is the engineer to whom we owe, directly or indirectly, nine-tenths of the comforts and luxuries of our lives? Luxuries, did I say? Necessities, rather. For does not the engineer bring us, perhaps from some far-distant lake, the very water we wash in? Is it not by his beneficent help that we are enabled to wrest from nature the treasures that lie hidden in the earth—the coal, for instance, that in one form or another gives us heat and light? Does he not make the iron and steel that we use so often in the day? Does he not see that we are clothed and fed?—for he it is who spins and weaves cloth, and he it is who builds ships, harbours, railways, canals, and other works, so that the corn that makes our bread shall reach us quickly and cheaply. Truly, when we begin to talk of the conquests of engineering, we mean the conquests of civilization.

This book is about civil engineering, though, strictly speaking, there is no such thing. Nowadays, when people speak of civil engineering, they mean those particular branches of engineering that deal with the science of bridge building, or of canal building, or of harbour or dock engineering, or of some other great work of public utility; and it is through the undertakings of these branches that this book accompanies you. As a matter of fact, the engineer who designs locomotives or steam engines is a civil engineer, but he is more generally called a mechanical engineer, because the particular branch to which he devotes his energies has come to be called mechanical engineering; so it is with hydraulics, or pneumatics, or electricity, or with mining, to name a few of a great number of subjects that come within the scope of the engineering faculty. Engineers who devote their energies to making pumping machinery, for instance, are still civil engineers; and civil engineers are, or should be, pumping engineers, and electrical engineers, and all other sorts of engineers. I mention this because people are apt to run away with the idea that a civil engineer is a superior sort of person to his brother that makes, let us say, brewing machinery, or sugar-refining machinery, or printing machinery. That, of course, is rubbish. All the same, there may be a great difference between the engineer that makes printing machinery and the one that builds bridges and waterworks and docks, for, though they both work on principles of physics and mechanics and mathematics, which are no more their property than they are yours or mine, the one may spend all his time and brains in perfecting one type of printing machine, while the other may be a bridge builder, called upon to face fresh difficulties and to solve new problems every day. Once you have made a printing machine, or a motor car, or a locomotive, you have something you can copy—with greater or less variation—until your products are no longer required. The modern locomotive is essentially the same as its queer-looking parent, which ran on the Stockton and Darlington Railway in 1825. Successive locomotive engineers have made it more efficient, more capable of performing its work; and the same is true of the printing machine, or the dynamo, or the gas engine. But, although he may learn valuable lessons from great bridges that other engineers have designed, the man who designs bridges cannot take these as patterns when he is called upon to carry a line of railway over a valley or over a river estuary, in the sense that one locomotive affords a pattern for all designers. The bridge builder cannot even copy his own bridges, for every time he builds one he is called upon to face new facts and circumstances—to fight his battle with nature with different weapons, and from different standpoints. Here, surely, we have the romance of engineering.

Let us suppose the case of an engineer who is called upon to build a bridge. He is an engineer of great skill and resource, and his advice has been sought by the promoters of a new line of railway. This railway, let us say, is in a far corner of the earth, and is to open up and develop a new country. Our engineer must first of all visit, or send deputies to visit, the site where the bridge is to be erected. It may be that the line has to cross a deep and wide gorge, as at Niagara, or the Victoria Falls; or the bridge may be required to cross a wide expanse of water, and at a great height, so that ships will be able to pass beneath it; or, instead of these possibilities, it may be in one of a multitude of situations, that we can easily conceive if we think of all the bridges we know, and the engineer cannot say beforehand, "This is just the place for a bridge of such and such a type, like that one that was built at such and such a place". One type, otherwise suitable, may be out of the question on account of the space to be crossed; another will not do, because the bridge is to be carried at such a height that it would be impossible to build piers successfully; a third type may be suitable, but may be cast aside because of the scarcity of skilled labour to erect it; and there may be difficulties in the way of transporting the materials that preclude the possibility of erecting still another form; and so on and so on.

You will see at once that no two bridges of any magnitude are built in exactly similar situations, or have to fulfil quite the same functions. You may observe a striking illustration of what I mean if you ever spend a holiday at Bangor or Carnarvon, and take a trip in a steamer down the beautiful Menai Strait. Spanning the Strait, and connecting Carnarvonshire with the Isle of Anglesea, are two beautiful bridges, almost side by side. One, a graceful suspension bridge built by Telford, carries the roadway; the other is Robert Stephenson's great tubular bridge—an imposing monster of iron, on tall masonry towers—over which thunder the Dublin boat expresses. You will, I hope, have made friends with both of these bridges before we have finished our journey round the world together; just now I want to explain that Telford's bridge could never have answered the purpose for which the tubular bridge was built, and that the latter would have been quite unsuitable for carrying the roadway, although either bridge could hardly be improved upon now, so far as regards its fitness to fulfil its own purpose.

One of the most romantic things in the whole romantic story of bridge building, with its difficulties and dangers, and the triumphing of mind over matter, is the fact that every bridge—and for that matter, every other engineering work—has to be thought out and planned as if there were nothing already in existence to guide and help the designer. If you think a minute, you will realize what this means. The principles on which a bridge is built—its theory, that is—are fixed as firmly as the law of gravitation, and the theory of the lever and the wedge; and though from time to time bold engineers have applied principles that their predecessors did not apply, or have employed them in a different form, *the principles are always the same.* In every case, however, they have to be separately applied and adapted in such a way that the particular form that the engineer devises is the best for the purpose of his bridge, and that none other is quite as good.

Let us go back to the case of the engineer who has to design a bridge for a new railway in a distant land. Suppose he has to carry the railway over a wide and rapid river, in order to avoid the necessity for making a wide detour and taking the line perhaps a hundred miles out of its way. Well, there are many bridges in similar situations that we can find without going outside the British Isles. There is the Forth Bridge—the largest in the world; and then there are the Tay Bridge, the Saltash Bridge, and the tubular bridge over the Menai Strait, about which I have just spoken. Why could not our engineer literally copy one or other of these? I have already told you the reason, but we might find an answer to our question by asking ourselves another one: Why do the four bridges just named represent four different types? Why should not the Forth have been crossed by a bridge like that erected by Brunel on the Great Western Railway at Saltash? or the Menai Strait by one like the Tay Bridge? Engineers do not build bridges of a particular type that appeals to them simply by way of making experiments; bridges cost too much money, and before they are built the people who have got to pay for them require to be assured that they will be absolutely satisfactory when they are built. Obviously there must have been some very good and consistent reasons that prompted the engineers of these four bridges to choose their designs. The answer is that the Firth of Forth could not possibly have been spanned by a bridge of the Saltash or the Menai type, any more than the Menai Strait could have been crossed by the Tay Bridge. Why? Well, to take two instances: the Tay is comparatively shallow, and there was no difficulty in building a large number of piers to support the short spans of its bridge; while the Menai Strait and the Firth of Forth are very deep, and the engineers found that there were practically only two spots on which it was possible to build piers to support the bridges—in the case of the Forth Bridge, a neck of land jutting out into the river and a small island in midstream; and in that of the Menai Bridge, two points at which the bed of the Strait was shallower than elsewhere. Further, it would be physically impossible to cross the Firth of Forth by means of a bridge such as that at Saltash, for the reason that if the Saltash span, 455 feet, were increased to the Forth Bridge span of 1710 feet, it would never be able to resist its own strains and stresses; it would, in fact, be so heavy that it could not possibly hold itself up!

So we see now that wherever and whenever a big bridge has to be built, the design that the engineer follows is governed by the local circumstances. It is not as though he could carry his bridges about with him, ready made, as he could a pump or a locomotive, and could say when he came to a gap in his path: "Now then, here's the bridge, put it across!" His battle with Nature is so dangerous and uncertain that he never knows where she may attack him, or in what way. He has to study his problem from every point of view, and then bring against her the particular weapons with which he can be certain to conquer her.

Now that I have made it quite clear, I hope, that our engineer cannot make up his mind what sort of a bridge he is going to build in a particular situation until he has reviewed all the possible circumstances that he will have to meet, let us see how he sets to work to discover what these circumstances are. I have already spoken of artificial reasons, such as leaving room for the passage of ships, which must govern the design to a considerable extent; but let us suppose that there is no such condition to be fulfilled in the case of the estuary over which it is proposed to build a railway bridge. We have, therefore, only to consider the physical or geographical conditions, and on them will depend almost entirely the type of bridge that we shall decide to erect.

First of all, then, we carefully study the formation of the ground, in order to find the easiest means by which the railway can approach the estuary, and this will help us to decide on the best site for the bridge; and here there are so many things to be thought of that, unless I just make a brief mention of some of them, we shall never be able to get through all the things I want to tell you about bridges before we get to the end of this chapter.

We mentioned the approach to the bridge, and you will see at once that this may have an important bearing on whether it will be easy or difficult to bring up the materials for building the bridge and the plant — the machinery and the tools that the contractor requires; and whether the proposed situation will add to the difficulty of housing the great body of workmen without whom the bridge could not be built, or of providing for them, feeding them, and keeping them in health, for there are some parts of the world that are so unhealthy that men could not live in them until steps have been taken to drain them, or to rid them of mosquitoes and other insect pests. You will see what terrible hindrances of this kind Nature may place in man's way when we come to speak of the most ambitious of modern engineering conquests—the building of the Panama Canal.

But let us get to the bridge itself. Here again we must think of the approaches; the engineer's design may be considerably influenced by the amount of room in which he can build the abutments that will support the bridge at its ends. He must be an expert geologist, for he will have to find out whether the ground is capable of safely carrying great weights, and whether it will require much blasting or excavating before a footing can be made for the abutments. Here he has to look below the surface, for things are far from being what they seem to be, or what one may expect them to be, in the crust of our wonderful earth: and a slight error in estimating the nature of the ground may make an enormous difference to the cost of the bridge, by forcing the builder to adopt other methods of dealing with difficulties than those that he originally intended to employ; or it may even render the execution of the bridge impossible.

But it will generally be the nature of the river itself that will most strongly influence the engineer's ultimate choice of design. If the river is very swift or very deep, it may be impossible to erect in it piers to carry the bridge, which then must be thrown across the gap in a single span, such as those that have been built at Niagara and Victoria Falls, to name two typical instances. If the river to be spanned is a very wide one, it may not be possible to bridge it with a single arch, and in certain cases it is conceivable that it might be necessary to divert the river, or to cause it to become shallower or less rapid. It would have to be a very exceptional case before such a gigantic work would be done, and it would probably be cheaper to take the railway to some spot where the river could be more easily crossed. Nevertheless, the engineer is so bold and so resourceful that, financial reasons apart, there is probably no situation in the world that he could not bridge, if he wanted to. Fortunately, however, the engineer is able to carry his bridge piers down through very deep water indeed. (I shall tell you presently the story of the Hawkesbury River Bridge, of which the piers had to be sunk through 40 feet of water, and 120 feet of mud below the water.) Indeed, it is a good deal simpler to build bridge supports through many feet of water than it is to build them through a much smaller depth of some of the substances that lurk hidden beneath the water, ready to spring very unpleasant surprises on the long-suffering bridge builder. Think of the task of going down through mud, mud, mud, for the depth of a good tall house! And down through the mud the builder must go, until a hard bottom of rock or clay is reached on which the piers to support the great structure of the bridge may safely rest. Instead of mud, the piers may have to be carried through sand or gravel; or the workers may reach a bed of hard clay—after months, perhaps years, of weary toil—only to find that it is unstable, and that immediately beneath it is more sand or gravel! All these things, and many others, the engineer must consider before he can decide what sort of bridge he shall build; and of all these things he must have knowledge as absolute as he can obtain. Nothing must be left to chance, or disaster is pretty sure to befall the greatest and ablest work of man.

Our list of the things that the engineer has to keep constantly in mind has become pretty formidable, although we have only touched on a very few of the more important. Let us suppose one more condition, which may have a deal to do with the design of a bridge. On some estuaries, and in other places as well, for the matter of that, storms of great violence occur more frequently than elsewhere, as we all know. The Firth of Forth is such a situation, and the Forth Bridge has to weather gales that wreck the boats that sail under it, and blow men off their feet—gales, in fact, that you and I would not care to be out in, unless we were particular friends of the grim nor'-easter. But the Forth Bridge never complains, and never will complain. Why? Because the engineer that designed it took these terrific gales into consideration. He could not tame the gales, but he could, and did, see to it that his bridge should stand against them. Other bridges nearly as big, and just as sound and as usefully fulfilling their purposes, would very soon be blown to pieces if they were taken from their own sites and put in the Firth of Forth; but the Forth Bridge was designed to offer as little resistance as possible to the wind, and to stand up against the hardest wind that will ever blow.

What a wonderful science, then, is this one of bridge building, and how little we appreciate the difficulties the engineer is called upon to face, or with what bravery and persistence he copes with them! A famous engineer once said that people do not take very much notice of bridges, however noteworthy they are, because they are so soon crossed. A great ship in which we take a voyage appeals to us with far more romance, because we are brought more closely into contact with its mysteries and magnitude, or because we are consigning our lives to its safe keeping. As structures, bridges are just as wonderful creations of man as are steamships, and every time we cross a bridge we are depending for our safety on the wit of the men who designed and built it. If you pause to think of this when next you look upon a bridge, or are whirled across one in a train, the marvels of bridge building will have a new significance for you.

It is clear that a very careful survey of the ground has to be made before any work can be started on a bridge, and even before the engineer can finally fix in his mind's eye the particular form that will eventually arise. The actual measuring of the ground with levels and theodolites does not differ very much from that which is employed by the men who survey the ground when they want to cut new roads through fields, or by the architect when he wants to build a new house. But when it comes to planning accurately on paper distances in the water between piers that do not exist, surveying presents a prettier problem, and we are inclined to ask, "How is it done?" as though it were a conjuring trick. The engineer has to build piers in the water—a thousand feet or more apart, perhaps; and he needs to know within an inch that these piers, when they are built, will be *exactly* in their right positions, so that the superstructure will *exactly* rest on them at a predetermined point. You cannot accurately measure water with an instrument of the tape-measure variety, as you can dry land; and you can't build a bridge first and then cut a bit off if it is too long, or add a bit if it is too short. Next time you pass a pond or a river design a bridge, in imagination, to cross it, and you will find that the answer to "How is it done?" is a good deal more baffling than the discovery of most conjuring tricks. The engineer has to solve that problem every time he builds a bridge across a sheet of water, and he is not allowed to make any mistakes; so he calls to his aid the science of trigonometry, or measurement by angles. If you have made acquaintance with this science—it is one of those tantalizing things that floor us when we are at school, and hit us at every turn when we have left—you will know all about it; if you have not, you must remain in ignorance for the present, for if I entered upon it here you would say I was dry.

But there is one aid to the measurement of bridges that is sometimes employed, and that is more interesting than trigonometry, and so may be mentioned. When the piers have been built above water level, the builders desire to satisfy themselves that they are actually the correct distance apart, and on the correct middle line of the bridge, as marked on the plan. The trigonometrical measurements are, of course, checked, but the engineer has recourse to a practical means of measuring, as opposed to a theoretical. He makes what is, in effect, a giant tape measure. He first of all measures out, on a straight stretch of land, a distance exactly equal to that which he has to verify. At each end of this space he sticks into the ground, perfectly straight upwards, a tall post, provided on the top with a knife-edge similar to that on which rests the beam that holds the pans of the weighing scales in the kitchen; and from one post to the other he stretches a length of very fine steel wire. The ends of the wire are carried over the knife-edges, and are weighted so as to keep the wire taut. Then, at the exact spots where it touches the knife-edges on the posts, he makes marks on the wire that he will be able to recognize again. As there is bound to be a little sag in the wire, its amount is carefully measured and recorded. The marked wire is afterwards stretched between the points of the bridge that it is desired to verify, and shows at once whether the work has been built strictly in accordance with the plans. Of course, the same amount of sag must be allowed for as when the wire was measured on land, and the temperature, as well as other matters, has to be considered. This method was used when the Forth Bridge was being built, to verify the distance between the centres of the two great towers, and showed an actual discrepancy, or error, in the building of the towers of six inches. This does not seem very much to be out in a distance of 1710 feet—a mere 3420th part, in fact—but it was sufficient to cause the engineers some trouble to put it right.

Now that we know something of the manner in which the site for the bridge is measured, and how the measurements are checked when the work is actually in course of construction, let us see what sorts of bridges there are from which the engineer may choose the one that is most suitable for a particular situation. We know that there are many different kinds of bridges—we cannot help seeing that every time we go for a ride in a railway train; and we know also that every bridge is where it is because it, and it alone, is the best adapted for the work for which it was put up. There are big bridges and little bridges, iron bridges, brick bridges, steel bridges, and stone bridges; some look very light and graceful, some are solid and ugly; the shapes of some are quite familiar to us, because there are so many alike, but others look very strange and unusual.

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BUILDING THE FORTH BRIDGE

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How can we distinguish these different kinds so that we may know what they are when we take our walks abroad? First of all, let us take the bridge that we see most often—the common and generally ugly bridge that carries a railway over the road; the bridge that looks as smug and conceited as a boy that thinks he is much better than his fellows. This sort of bridge is a girder bridge, because the line is carried across the opening on girders, which have no intermediate supports. The girders may be made of cast iron, or they may be made of steel plates riveted together so as to form an unvaried whole. A girder, the dictionary tells us, "is a beam required to support a weight that acts in a downward direction", and the great majority of bridges are girder bridges of one sort or another. When the sides of a bridge present solid faces to you, through which you cannot see, it is said to be a plate girder bridge, because it is built of steel plates; when the sides are open, like a trellis work, it is a lattice girder bridge, and is built up of narrow pieces of steel fastened together in such a way that they form a structure as strong as though it were solid, but a great deal lighter. Some of these lattice girder bridges are very big indeed, and we shall meet a few of them later on.

A girder is a beam, says the dictionary, and it is on the principle of the beam that most bridges are built. A beam, of course, is not necessarily a girder: a plank put down to enable you to cross a brook is a beam, but a plank is hardly a girder.

A space of a hundred feet may be crossed by a girder made all in one piece, or the same space may be spanned by a beam composed of several small girders riveted together. When Robert Stephenson was wondering how he would carry the Chester and Holyhead Railway across the Menai Strait, which the sea had thoughtlessly put in his way, he remembered the beam, and built his great bridge after its nature. The Menai Bridge is called a continuous girder bridge, and in principle is simply an enormous beam with a hollow centre. Some girder bridges are called "bowstring", and are shaped so —the bottom outline forming the string, and the top one the bow. The idea of this shape, which has many variations, is to make the depth of the bridge proportionate to the strains it has to suffer and the load it has to carry; in other words, the bridge is deepest and strongest at the points most liable to injury.

Some bridges spring from side to side of an opening in a single arch, without any intermediate support. In the arch the weight of the bridge, and the multitude of strains and stresses set up in it, are carried to the abutments on which it rests at either end. Some of the most magnificent bridges in the world are arches; and if a railway has to cross a gorge or ravine that is too wide to be crossed by a single girder, and too deep to allow piers to be built, it is pretty sure to be spanned by an arch. If not an arch, then a suspension bridge—which might almost be described as an arch upside down—will be thrown across the gap; for by this means, too, great widths can be spanned without the use of piers. The Brooklyn Bridge, which connects New York with Brooklyn on Long Island, is the largest suspension bridge in the world. It was opened in 1883, and has a span of nearly 1600 feet, the total length of the bridge and its approaches being over a mile. The bridge is suspended by four huge cables of steel wire, which are carried over high abutment towers of masonry, and firmly fixed, or "anchored", to the shore. Each of the cables is 3572 feet long, or say, more than five-eighths of a mile; and each is capable of supporting a load of 12,000 tons without breaking.

But we need not go to America to see suspension bridges. Although our cousins across the Atlantic can claim the finest example, there are some very fine ones in this country. I have already mentioned the one that Telford built in 1825 across the Menai Strait; we should always look up at this with admiration, for apart from its airy grace it was at the time it was built a far more formidable undertaking than a much bigger bridge would be to-day. Then there are the suspension bridge at Clifton Gorge, Bristol, and others that should be familiar to you if you live in London—those at Wandsworth and Hammersmith.

We have come nearly to the end of the list of the more usual types of bridges, but we have so far omitted to make any mention of a very important type indeed. What about the mighty Forth Bridge? What sort of a bridge is that? Doubtless you have heard it spoken of as a cantilever bridge, but what exactly is a cantilever? Perhaps you will laugh on being told that the mantel-shelf is a cantilever, and the arm of the iron standard that carries the electric light in the street; but these things are cantilevers none the less, though of a primitive kind. A cantilever is, in fact, less formidable than its name, for it is nothing more than a bracket. Cantilever bridges are built when there are great difficulties in the way of holding them up while they are being made.

In most cases girder bridges are built and completed span by span, this work being done on shore. Meanwhile, the piers are being built in the water, and when they are ready the spans are launched into the positions they are to occupy, either by rolling them forward, or by lifting them up by some means or other and then letting them down into their proper positions. Obviously this process becomes impossible when the space is a very wide one—say over 500 feet—for a bridge span is so heavy and awkward a thing to handle that to move it is difficult and dangerous. Suspension bridges are built by carrying the cables across the opening a strand at a time, joining them together, and then fastening the bridge to them, bit by bit; but then suspension bridges are not suitable for all situations—they are inclined to be springy and wobbly, for instance, as one might expect. Most arch bridges are built on a temporary support or scaffolding called "centering", and sometimes by means of an overhead ropeway, which carries the materials to it plate by plate, ready to be joined on, as was done in the building of the bridge over Victoria Falls. In such a case as the latter the bridge is built on the cantilever principle, which simply means that it is built out from both sides simultaneously, after the manner of brackets, each bracket being maintained in perfect balance.

To make this clearer, let us copy the way in which the Forth Bridge was built. It will not be a very accurate copy, because we are going to use matches instead of steel plates and girders, while the tablecloth will be our Firth of Forth, and two match boxes will answer the purpose of the great piers between which we have to erect the bridge; but our illustration will give us a good idea of the principle of the cantilever. First of all, we must pretend that the middle span of the bridge is equal to a length of, say, five match sticks, and that we cannot join them together before we put them in position between the middle towers; we can make these towers by sticking matches through holes in the tops of the boxes so that they will stand straight up, though this may be rather a waste of match boxes. Obviously we must build the girders out match by match, in order to span the opening; but we shall find that when we have joined up two or three match sticks in a horizontal direction, thus |‾ ‾ ‾, their weight will become too heavy for the "tower", or upright stick, which will topple over. Instead, then, we must build out on both sides at the same time, thus ‾|‾, and then thus ‾ ‾ | ‾ ‾, for in this way the structure is kept in a state of balance, and the arms or cantilevers will not topple over, because the weight is equal on both sides. The work is carried out simultaneously from both towers, until at last the girders meet in the middle, so \‾ ‾ | ‾ ‾ ‾ ‾ ‾ ‾ ‾ | ‾ ‾/, the diagonal lines at each end representing the banks of the river that is being crossed. This, then, is the principle of the cantilever, which has, however, to be supported and strengthened in such a way that it will not break down by reason of its own weight.

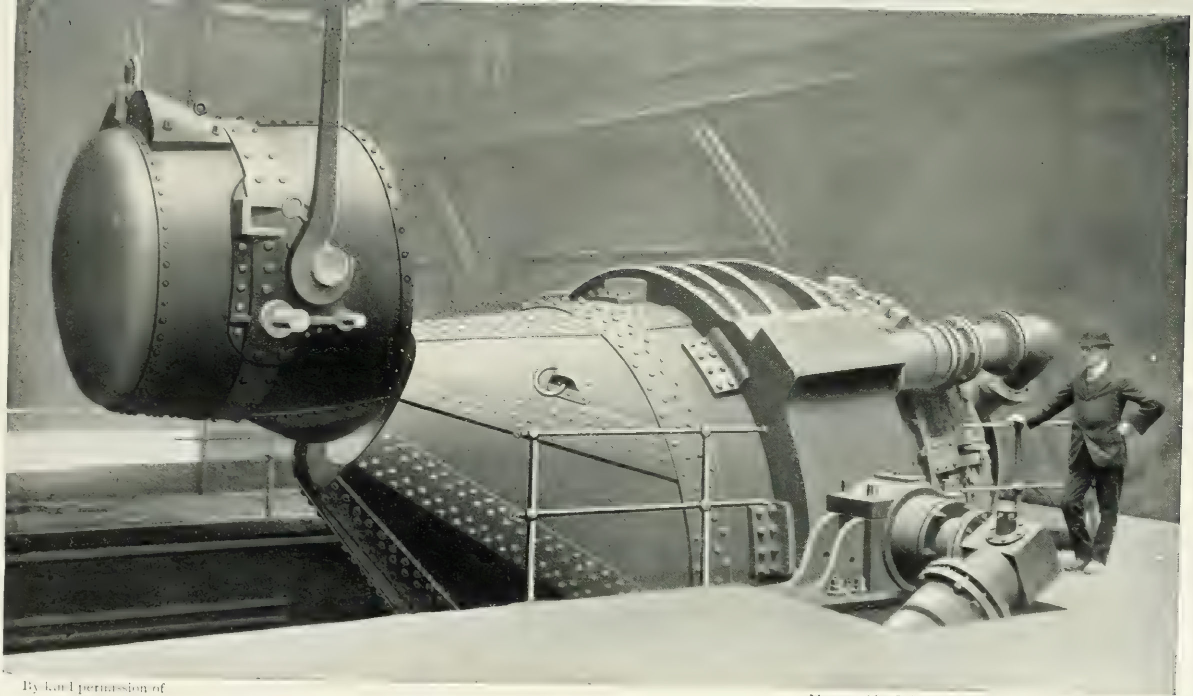
Here we touch upon another of the great problems that confront the engineer every time he wants to build a bridge. He has to make exact and elaborate calculations to find out, not merely whether his work will be strong enough, say, to carry safely the trains that will pass over it, but also the exact strength and size of which every little piece of material in the bridge must be made. Before the first stone can be laid or the first rivet closed, the length, breadth, and thickness of every girder, plate, and stay have to be determined. The material has to be submitted to most critical tests; it is put through machines, which hammer it with monstrous weights, and draw it out, and bend it down, and do all they can to destroy it. If it cannot withstand the shocks and strains to which it will be subjected in the finished structure, it is cast aside. Think of the trouble of calculating all these strains and stresses, and allowing a proper margin for safety! The engineer has to be able to say with certainty that, unless there is some hidden fault in the material, the most insignificant rivet in a bridge will not break or shear or bend until it is subjected to a definite strain, for the breaking of quite a little thing may bring about the collapse of an enormous structure. When next you cross a bridge, or stand under some lofty steel roof, think of the care that has to be expended in the design of its smallest detail, and the means by which that care is exercised, and you will have an increased respect for the painful but useful science of mathematics.

It might at first sight, perhaps, seem a comparatively easy matter for the engineer to form a bridge strong enough to carry the trains that will pass over it, by making each one of its members of sufficient stoutness; and this is indeed just what he has to do, once he has calculated the load that the bridge will have to support. But the problem is really far more difficult than it appears to be, because every piece of steel that is added to the bridge makes it heavier, until there comes a point at which it is so "strong" that it cannot hold itself up. Professor Claxton Fidler tells us that the heaviest train that crosses a great bridge is an infinitesimal addition to the weight of the structure, and makes hardly any difference to its internal strains; and that if the Forth Bridge had been commenced upon the lines of Brunel's Saltash Bridge, it would soon have shown itself to be an impossible project, for the weight of girders of the

Saltash pattern would have formed a load very much greater than they could carry.

I expect that by this time, if you had not before thought of these things, you are beginning to realize that the bridge designer is a very much harassed gentleman, whose life can hardly be much more enviable than that of a schoolboy "on the grind". As a matter of fact, the engineer will tell you that his work gives him the keenest delight; and that although he has to learn lessons constantly, they never pall, as they are apt to do when we are at school. The secret of his pleasure in his work is worth remembering; it is that he is employing his brain for the betterment of his fellow-creatures—not groping blindly, but using his faculties to discern means to apply to the solution of mankind's difficulties the knowledge of the chemist, of the physicist, of the mathematician. We cannot all be builders of great bridges, but the little culvert that carries the babbling brook under a railway is just as important in its way, and needs just as much care and forethought in its making.

Before we leave the subject of the calculations that the engineer has to make, we must dip just a little more deeply into the sea of perplexities that surrounds him while he is performing this necessary work. The weight of the load that the bridge must carry, the weight of the bridge itself, and the strength of its parts, are the most obvious things that he has to discover before he can finish the



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CHARGING A STEEL CONVERTER

The Converter is seen tipped into position for receiving the charge of 15 tons of molten iron from the ladle.
Note the large air pipes leading to the tuyeres.

design; but there are also what we may call external influences, which are less apparent. Bridges have to be made strong enough to withstand the winds that Nature, as though angry at being fettered, hurls against them. Some quarters of the globe are comparatively free from serious gales, and in them the engineer does not need to allow so large a margin for safety from wind pressure as in other places where storms are more frequent and severe. Indian bridges have to face the terrific force of the monsoon. London has no monsoon, but it can blow pretty hard in London at times, and the Tower Bridge, which offers a large exposed surface to the wind, was calculated to withstand a wind pressure of 56 pounds to the square foot, which is the allowance generally made in Great Britain. In a heavy gale the Forth Bridge suffers far more severe internal strains than those set up by the passage of a train.

Then the action of heat and cold has to be allowed for. You know that all metals expand with heat, and contract when the heat diminishes; and the engineer has to take careful steps to provide for this. In some bridges an arrangement called an expansion bearing is placed on the bed stones on which the girders rest; in others the ends of the girders are left free to move over rollers, so that they can contract or expand without hindrance. It is said that when the Menai Bridge was being tested by having heavy trains passed over it, before it was opened for public traffic, it was found that the weight of a train—350 tons—caused a smaller deflection, or movement of the bridge from the true horizontal, than could be measured after half an hour's strong sunshine!

Our hurried glimpse at the preliminary work that has to be performed before the engineer can build a bridge has sufficed to give only a very rough idea of the immensity of the labour of bridge building. Remember, not a stone has yet been laid, not a single workman engaged, and yet the designer's work is not finished. Finished! Hardly commenced, rather should we say. At this stage the bridge exists only in the engineer's imagination. It has to be conveyed in all its details to the men that are to build it; it has to be built first on paper, and then in steel and stone, and the preparation of the original drawings is not the least wonderful part of the wonderful science of bridge building. Professor Claxton Fidler, in a most interesting book called *Civil Engineering*, shows us clearly how far a great bridge is a child of its designer's brain. He says: "The engineer is just commencing the design of some new structure in a totally new situation. He has before him a perfectly blank sheet of paper, and nothing more. Upon that sheet will presently appear a drawing which is not copied from any older example, and which, indeed, will not represent anything in the world that *is* or *has been*, but something that is to be. Nobody knows as yet what shape the picture will take, for the man himself does not yet know. He would tell you, perhaps, that a week ago his mind was almost as blank as the paper; but he has been considering the conditions of his problem."

If the working drawings of a bridge were set before you, and you were asked to explain the apparently puzzling mass of lines, and curves, and angles, you would probably give up the task in despair. But the drawings are the workmen's instructions, and tell them clearly and exactly what to do. Every detail, every joint in plates and rods, every rivet and bolt have to be shown, together with the exact sizes to which they are to be made. The preparation of the drawings may keep a large number of draughtsmen actively employed for a long time. The Vauxhall Bridge built recently over the Thames, in London, required no fewer than fifty lithographed copies of the book of plans to be made. The book contained 80 pages, each page being a yard square—yet the Vauxhall Bridge is a comparatively small one. Imagine what must be the task of making drawings for enormous structures like the Menai and Forth bridges!

Before we close this chapter, let us take just a hasty peep at the stuff of which most modern bridges are built—steel. What visions of modern alchemy the word conjures up in our minds! Deadly guns, ponderous battleships, whirring dynamos, thundering locomotives, down to the pocket-knife or the homely needle, turn where we will, we are confronted with the glint of steel. To the inventors of the modern methods of making iron into steel must be given a large share of the credit of the triumphs of engineering. It is now more than sixty years since the late Sir Henry Bessemer, in England, and William Kelly, in America, brought out processes that were destined to revolutionize the iron trade. Steel had, of course, been made for centuries before that; this widely used metal is simply iron transformed into a harder, tougher, and more useful substance by the addition of carbon. But before the converter was invented, steel-makers had to use a laborious and costly process to produce an expensive metal of very uncertain quality; whereas to-day the quantity of steel produced depends only on the quantity of iron available. I am not going to trouble you with a lecture on metallurgy, but it is interesting to remember that no one quite knows what iron is. We know that it exists in almost everything, that it is in our bodies, that we are ill if we have too much of it, and die if we have too little; we know also where to look for it in workable quantities, and that learned men, to whom we owe great thanks, can tell us a great deal about its composition and peculiarities. Beyond that, it remains for future generations of scientists to tell us exactly what iron is, and how it has been produced in Nature's manufactory.

For the present, therefore, let us away to man's manufactory, to see this wonderful metal being turned into steel. Someone once said of steel-making that it is the noisiest business in the world. However this may be, it is certainly the most terrific and awe-inspiring. The steel is made in a converter, a huge iron pot, in the bottom of which are arranged a large number of nozzles, or tuyeres as they are called. The pot is pivoted so that it can be tilted, and is placed under the blast furnace in which the iron is melted. When the steel-maker is ready for a "blow", as the process of conversion is called, the molten iron—sometimes as much as 10 or 15 tons—is poured into the converter, and a tremendous blast of air, supplied by a blowing engine, is directed into the liquid mass by means of the tuyeres. With a roar that is terrifying enough to make the hair of Vulcan himself stand on end, and that produces in him who sees the process for the first time a strong inclination to run away, the great mass of white-hot metal boils and seethes, and becomes most violently agitated as the air rushes through it and burns out the impurities. Louder and louder grows the volcano, and hotter and hotter it becomes, while from the open mouth of the iron crater rushes, almost in a solid column, 50 feet, perhaps 100 feet high, a mighty mass of sparks, which in its magnificence eclipses the largest firework display you ever saw. And throughout this violent upheaval calmly stand the men in charge, watching with critical eyes. After a few minutes the blast of air is stopped, and the proper amount of carbon is tipped into the converter; the great pot is then moved on its axis, and discharges its fiery contents. Once you have seen it, you will never forget the dazzling whiteness of the molten steel as it flows into a mighty ladle. A poker dropped into it would melt like butter. If a man went too near, he would be singed to a cinder before he could run away; if he fell in, the gleaming river would consume him in a flash, and not a single particle would be left of him. Thus by titanic methods indeed is steel made; and if ever you have the opportunity to visit steelworks, you will witness the most furious of man's servants. The dimly-lighted sheds, peopled by half-naked men, who look like pygmies in the mysterious semi-light that comes from the furnace; the roar of the converter, the hiss of the sparks, and the terrible stream of white-hot steel form a picture and an impression that will probably always remain with you.

When the steel is tipped out of the converter, it runs into an enormous ladle, as I have just said, and from this again it is poured into moulds of oblong shape, in which it cools into ingots or blooms. It is from these that the plates, angles, bars, &c., that go to the making of a bridge have now to be made. The blooms are made white-hot and passed to the care of gigantic rollers, which revolve one over another in a long line. The first rollers seize the bloom and squash it flat, the next squash it flatter still, and so on and so on, until it is the right shape and thickness. After this it is passed to a machine that planes its ends with as much ease as though, instead of a steel plate, it had to deal with a slab of putty. From this gentle instrument the plate may then be taken to another machine, which will drill in it, in a few seconds, and in a single operation, as many holes as may be required; or, instead of being drilled, the holes may be punched out, though this process is seldom adopted, because it tends to weaken the plate. Curiously enough, it is easier and cheaper to punch the holes than it is to drill them, although one would think that the reverse ought to be the case.

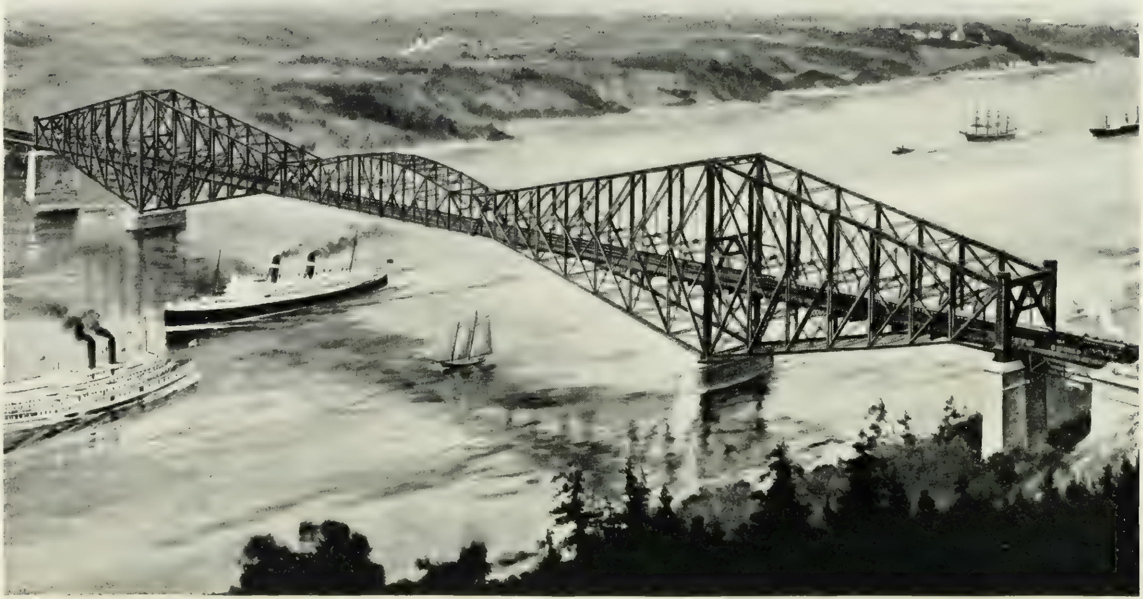
But many pieces of material that are not plates are used in the making of a bridge, and it is quite impossible even to mention them. We may, however, say a word for the gigantic hydraulic presses that forge "angles", and make flanges on girders while they are cold; and for the less ponderous and more active machine that is fed with bars of steel at one end and at the other disgorges completely finished rivets.

CHAPTER II

Machines for Building Bridges

Not the least wonderful part of modern bridge building is the making of the piers on which the structure rests. In the last chapter we saw how largely the difficulty of building them, or the absence of difficulty, is likely to influence the engineer's choice of design; and in the present chapter I propose to take some famous bridges and tell you the story of those parts of them that you cannot see. Our story will not be the less interesting on this account. Hidden deep down in the water, and perhaps many feet below the floor of river or ocean, are monuments of engineering skill and ingenuity. If you like, you may think of them as monuments to the memory of brave men, who died in the engineers' encounters with the forces of nature; or, what is better, you may regard them as emblems of man's mastery. Whichever view you take, you must not forget that every bridge has its heroes—humble heroes that have given their lives in the cause of progress; for no battle with wind or wave or treacherous sand is fought without some sacrifice of life and limb.

Before we make acquaintance with the strange



ST. LAWRENCE BRIDGE, QUEBEC

This great cantilever bridge has a total length of 3228 feet. Its building was dogged by disaster, the huge main span of 1800 feet – 90 feet longer than that of the Forth Bridge—being twice carried away whilst being raised into position.

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things that men do under the water, however, let us be introduced to the contractor. This gentleman is a very great person indeed, for it is he who has actually to build the bridge, and has to face, not in theory or on paper, but in grim reality, all the dangers and difficulties of rearing the great fabric from the plans of the designer. He contracts to undertake the building of the bridge for a certain sum of money, and to have it finished by a certain time. He may make a fortune out of his work, or he may make himself bankrupt. If he has not got the work finished by the promised time, he has to pay a fine for every day he is overdue; and although, of course, he thinks he knows before he offers to do the work just how much it will cost and how long it will take, he can never tell what sort of surprises may be sprung upon him in the way of unforeseen difficulties. In the early days of great engineering works, before engineers had acquired the great experience they have now, a single tunnel or bridge or cutting has ruined two or three separate contractors. Nowadays, fortunately, the builder is generally more successful in his undertakings, and actual failure to finish works once begun is almost unknown.

It is not until we come into actual contact with the contractor and his methods that we realize what a vast undertaking is the building of a big bridge. Then, when it is possible to get an idea of the amount of labour, time, and money that has to be expended, apart from the constant vigilance and resource that require to be exercised, one is almost appalled at the magnitude of his work. It may involve the expenditure of millions of money, it will demand the service of any number of workmen from 500 to 5000, and it will draw upon the resources of a hundred industries and a dozen countries. The building will call for a division of labour equal to that in a good-sized town, for men of all trades will be drafted into the work: carpenters, sailors, masons, ironworkers, steeple-jacks, divers, stablemen, engine-drivers—it would take a week to think of all the people that will be engaged in it, and we will not attempt the task. The work may be one situated in a thinly populated district; or to the actual difficulties of erection may be added those of housing a large army in an inhospitable climate. Houses for the workmen to live in, schools, and churches have to be built, and a proper water supply has to be ensured. In a little time, veldt or tropical jungle, smiling cornfield or stagnant marsh is converted into a busy, industrial town. Locomotives puff hither and thither, noisily shunting trucks filled with all manner of strange merchandise, parts of engines and weird machinery, bricks and stone, food for the workmen, material for the bridge. Giant cranes, with long straddle legs that carry them high above the trains, are swinging plates and girders into orderly stacks. In one great corrugated-iron shed, put up a couple of days ago, a mighty engine is generating electricity. In others, titanic machines are drilling and shearing plates, forging rods, and making bolts and rivets. A little farther away is a steam sawmill, which, if one may judge by the noise, is doing its best to cut up every tree that ever grew. And throughout it all sounds the clang of a thousand hammers, the soughing of a hundred steam engines, the *clank, clank* of endless trains of trucks. In a word, one's senses are so bewildered that it is impossible to grasp anything clearly, beyond the fact that all the noisiest trades have been let loose in a spot where a few weeks ago all was peaceful, except for the quarrellings of birds, beasts, and insects. But this chaos of sight and sound is nothing; the engineers are only getting ready for their work.

Let us go down to the waterside, and see what is taking place there. We find that the activity is just as great. Men swarm like ants along a half-finished breakwater, which is to form a temporary harbour. Steamers are vying with the trains in the rapid and incessant discharge of cargoes; tiers of barges, stacks of plates, mounds of all sorts, crowds of working men and teams of horses, clouds of smoke; rattlings of chains, screams of whistles, shouts of men, clangings of hammers—one would think that not one but a hundred bridges were being built!

Looking across the great stretch of water that is about to be saddled by the help of all this noise and bustle, we notice in midstream an isolated barge, with a strange-looking apparatus on its deck. If we look more closely, we shall see that two men are turning what appear to be winch handles. This is the diving barge, and the men at the handles are pumping air to the divers that are examining the bed of the water, or perhaps preparing it for great cylinders, which will be the first step in the growth of the bridge.

I do not think that you would care to be a deep-sea diver, and I am quite sure that I should not. At all events, the first experience must be rather unpleasant. Some of my readers, no doubt, know what the helmet diver's dress is like; but for the benefit of those who do not I will briefly describe it. First of all, the diver puts on a complete suit of indiarubber, made all in one piece; then come thick woollen socks, and over these boots in which one would not care to play football, for the sole of each carries 14 pounds of lead. Then come a heavy metal collar and shoulder-piece, over which two weights, each of 40 pounds, are slung. After that the helmet, which weighs another 30 pounds, is screwed on to the metal collar; and thus equipped the diver is helped over the edge of the boat on to a ladder. Before he goes down, however, a thick glass "window" in the helmet is fastened down, and men begin to pump air. Once the diver is under water, the air pressure is increased as he gets lower and lower, in order to counteract the outward pressure of the water. Sometimes divers work at depths of 100 feet to 120 feet, but at such depths they are unable to stay down very long.

On the bed of the ocean or of a river the diver has sometimes to face great perils. He may be carried off his feet by currents or buried in shifting sand, or his air tube or life-line may become cut or entangled. Sometimes he has to fight for his life with some fierce sea creature, though this happens more often in stories than in real life, for the denizens of the deep are usually more frightened of the diver than he is of them. A diver once told me how, owing to some accident, the flesh of his thigh became pinched in a fold of his dress while he was at a great depth. The pressure of the water was so great that, although he tried his hardest to do so, he could not move the fold, and he suffered the most intense agony until he could be drawn up. When the dress was taken off him it was found that a large piece of the flesh of his thigh had been pinched out as completely as though it had been cut with a surgeon's knife.

As illustrating the great danger of the possibility of the entanglement of the air tube and life-line, preventing the diver's return to the surface, Mr. Francis Fox, a well-known engineer, tells a story which I am going to repeat, as it gives a good idea of the terrible experiences that sometimes befall divers. Mr. Fox says: "An engineer was once engaged on a pier in India, and he, with two divers, was working below. The men in charge of the life-lines continually received signals from the men below to pay out more rope and tube. This they did until it was all paid out. But the signals were due to the rushing of the water through the ironwork of the pier, and were not sent by the divers. The result was, the air tubes and life-lines floated away to the current, and got almost hopelessly entangled with the staging and ironwork. The divers knew nothing of this until they endeavoured to return, when they found themselves caught. One man got alarmed, cut his life-line, slipped his leads, and came up to the surface like a cork; but the rapid change of the pressure killed him. My friend (the engineer) kept his presence of mind, and worked back along his line, disentangling and placing it in coils round his neck. Yard by yard he got it back, and in an hour's time succeeded in reaching the surface, completely exhausted."

All the same, the work of the diver has its pleasanter side, for Mr. Fox assures us that on a hot summer's day there is no more comfortable place to get a good sleep than the bottom of the sea, with your helmet on a rock for a pillow, especially if you realize that two men are grinding away at the air pumps, while another man has safe hold of your air tube and life-line.

We must leave the diver for the present, and get back to the manner in which that part of the bridge is to be built which lies hidden from view beneath the water.

There are several ways of sinking bridge foundations, and the method to be used in a particular case depends upon the depth of the water and the nature of the ground below the water. One of the commonest methods of laying bare the bottom of the sea or a river, which is employed in soft ground, where the water is not very deep, is the building of cofferdams. The cofferdam may best be described as a great paling, erected around the area on which the bridge piles are to arise. This paling is formed of huge piles of timber driven deep into, say, a river bed, so closely together that the water cannot get in. Sometimes the piles are tongued and grooved, after the manner of matchboarding, to make them watertight; or they may be driven in in double rows, one a few feet inside the other, the intervening space being filled with clay that has been "pugged" or beaten. The building of a big cofferdam is a very laborious and lengthy business, and costs a great deal of money—£8000 to £10,000 would be a moderate sum for a single dam of a good size. If the bridge is to have, say, six spans and five piers, five cofferdams must be built before a single stone can be laid, or a bucket of cement can be lowered, towards the construction of the piers. Thus you can imagine what a vast sum has to be expended in merely preparatory work.

It is most important that the piles for the cofferdam should be driven in perfectly straight, and each one close up against its neighbour. A steam piling engine is used for driving the piles, which have to be sent 30, 40, or more feet into the soft ground, being carefully kept in position during their descent by means of timber guides, or walings as they are called. If you live anywhere near the South Kensington Museum in London, or have an opportunity to visit that wonderful storehouse of treasures, you should go into the Mechanical Section, where you will be able to see a working model of a pile driver. You have only to press the button below the case and the model will work for you as long as you care to watch it. You will notice that the falling weight is lifted by the chain to a certain height and then released by a pawl, so that it falls heavily on to the head of the pile. This weight is called "the monkey", and may weigh anything from 2 to 5 tons. The pile driver is a very useful appliance, but it has a terribly destructive effect on the heads of the piles, and a pad of some kind is introduced between the "monkey" and the pile, so as to lessen the danger of smashing the latter. Probably the pad affords but little consolation to the poor pile, but, judging from the rapidity with which it jumps up and falls down, one would think that the "monkey" enjoys the fun. Steam hammers are sometimes used for pile driving, and many ingenious appliances have been invented to enable cofferdams to be built quickly and securely; and steel piles are also sometimes used.

When the cofferdam is completed the space which it encloses has, of course, to be pumped dry; but before this is done the great ring of timber piles has to be strengthened. In tidal waters valves are built, in order that the water inside may rise and fall with the tide, thus equalizing the pressure on both sides of the dam. If this were not done, the weight of the water left inside when the tide went down would burst the dam open; and, similarly, if it were pumped dry before it had been strengthened, the water outside would crush it as though it were a cardboard box. The strengthening of the dam is a gradual process, and is carried out in much the same way as you see when workmen strengthen the big holes they have dug in the roadway for the laying of pipes. First of all a little water is pumped out of the enclosure, and then cross timbers are placed from side to side of the dam; then a few more feet of water are pumped out and more struts are put down to the new level, and so on until the bottom is reached.

Although engineers can build large cofferdams accurately and strongly, they cannot foresee what hidden dangers will confront them when the work is done, and the forces of Nature very often have unpleasant surprises in store for them. In spite of careful construction and strong timber—the piles are a foot or more square—there may be somewhere a faulty place which will cause disaster, and there is always the danger from inrushes of water from hidden springs. A few years ago, when the new Vauxhall Bridge over the Thames in London was being built, an accident happened to a nearly completed cofferdam, undoing the work of months. On the evening before the mishap the dam appeared to be thoroughly sound; but there was a weak place somewhere, and in the night the water found its way in, tearing down one side and turning the structure into a complete wreck. When the workmen arrived on the scene in the morning, instead of the yawning chasm to the bottom of the Thames which they had left the night before, they beheld a pond, 30 feet deep, full of floating wreckage. It took a whole winter to renew the cofferdam, and the cost of the accident was about £5000. And it was not only water that found its way into the ruined cofferdam; for every time the tide came up it carried into the enclosure great quantities of mud, until at last there were 13 feet of it. Now, it happened that when the cofferdam was being reconstructed it was found that there was a faulty pile somewhere which let the water in, but it was impossible to find the fault owing to the depth of mud. The engineers were very much worried, for the leak was causing a serious delay to the work, and had to be stopped somehow. It was found at last by a plucky diver, who went down into the mud over his head. He was provided with a hosepipe, through which water was forced at a great pressure, and by playing on the mud with this he blew a hole, as it were, below him as he went down.

Far more serious in its results than the Vauxhall disaster was one that happened not very long ago on the Continent. A cofferdam had been constructed, and was being pumped and strengthened, when, owing to a rapid rise in the river, the water broke through and bore down the whole structure. The collapse of the piles, which were broken off like match-sticks, and of a staging above the cofferdam added a peril more terrible than that of the water, and of the thirty-four men at work when the disaster happened very few survived. Some were drowned, others were crushed to death between the timbers, and most of those who escaped with their lives were terribly injured.

The diver who carved his way through the mud in the Vauxhall cofferdam by means of a hose may seem to you to have adopted a strange method of achieving his object, but as a matter of fact the hydraulic jet is a very useful agent in driving piles, especially in cases where they have to go through sand. The next time you are on the seashore, if you run your walking-stick into the sand you will find that it will go down a long way quite easily. But if you first stamp hard on the sand with your feet for some minutes, you will find that it is difficult to get the stick in even a few inches. You will understand the reason for this readily enough; it is simply that the stamping forces the particles of sand so closely together that a hard, compact mass is formed: and the same thing happens when piles are being driven into sand, which at first thought does not seem a very difficult substance to get through. As the piles go down they beat the sand, and after a few piles have been lowered it becomes almost impossible to drive them down. It is then that a powerful jet of water is applied to the toe of the pile by means of a pipe attached to it, or a hose carried by a diver, and the sand is loosened and displaced by its influence, so that the pile sinks quite easily. With the water jet piles can be sunk to a depth of 20 or 30 feet in a few minutes, and should they get out of the vertical during the descent, they can easily be moved in any direction required by the same means.

The water jet has also been used on occasions to assist in the sinking of the huge cylinders that are used for building bridge piers when cofferdams cannot be made. What these cylinders are, and what are their functions, we shall shortly discover; but while we are in touch with the water jet I will tell you, by way of showing not only the power of the jet, but what an excellent servant of the engineer water makes, how it was once used by a clever engineer to rescue an enormous bridge cylinder from disaster. The engineer was Mr. Francis Fox, and the cylinder was for the making of one of the piers of Hawarden Swing Bridge, over the river Dee near Chester. The cylinder, which was a great circular wall, 43 feet in diameter, built of brickwork in cement, 5 feet in thickness, was being sunk in quicksand when one side became caught on a great boulder, which held it while the other side sank lower into the sand. The cylinder tilted over to such an alarming extent that many of those concerned in the building of the bridge gave up all hope of recovering it. Not so the engineer, who knew the power of a jet of water acting on sand, and felt that it would help him out of his difficulty. He caused a pipe with a nozzle to be lowered into the bed of the river close beside the boulder that had caused all the trouble, and when the pipe was connected with a powerful steam pump the stream of water issuing from the nozzle washed the sand away from around and beneath the obstruction, so that it quickly sank, and the cylinder righted itself. Mr. Fox, in a book called *River, Road, and Rail*, speaking of what the water accomplished for him, says: "By means of the water jet, this cylinder of brickwork, 43 feet in diameter, weighing 2500 tons, and which had canted over to such an extent as to cause dismay to many, was brought back into position within three-quarters of an inch of its desired place in a few hours, and it was possible to play with the great mass, and move it one way or the other exactly as one wished."

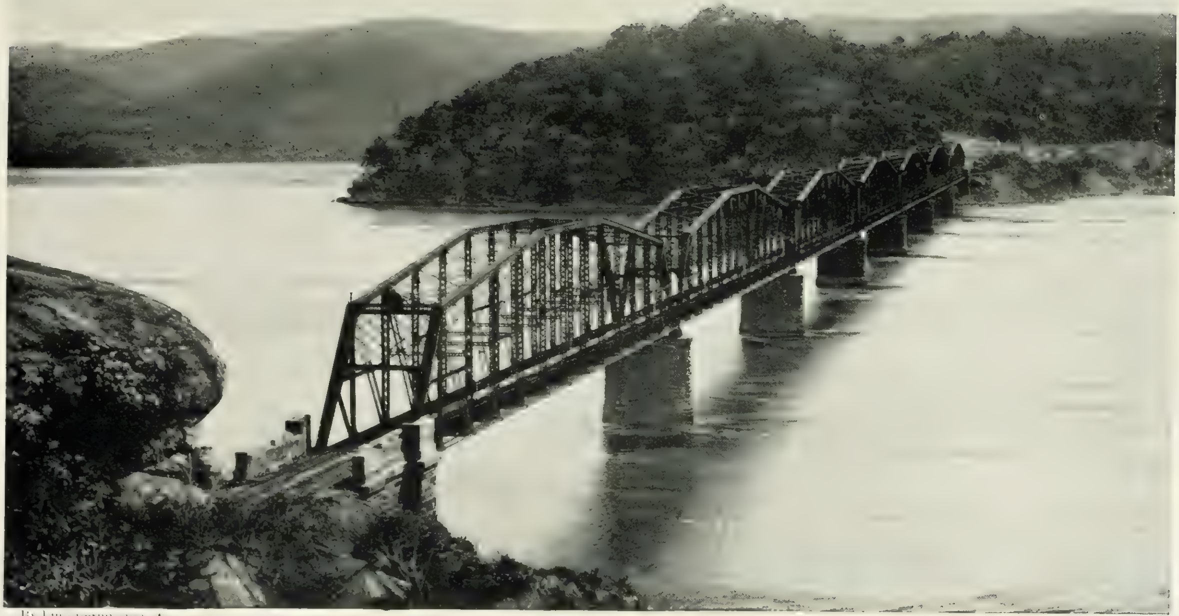
You will understand readily enough that it is only in comparatively shallow waters that cofferdams can be built. The piles of which they are formed are sometimes 50 feet or 60 feet long, but it is quite common for engineers to have to build bridge foundations at depths of over 100 feet, and in such cases they resort to the use of steel cylinders. These cylinders are called caissons, caisson being a word that is closely related to case, since both come from the French *caisse*, and both mean the same thing. A caisson is, in fact, simply a huge box, made cylindrical in shape, so as to resist better the pressure of the water, and built up of steel plates or cast-iron sections, bit by bit, until the engineer has made a vertical shaft down to the bottom of the river. Generally speaking, a bridge cylinder is distinguished from a caisson by being open at the top, for the caisson is closed in, so that the men who build the masonry upward have to work in compressed air.

One of the finest bridges in the world is that which crosses the Hawkesbury River in New South Wales. This bridge was built to enable through trains to be run between New South Wales and Queensland. Its construction was a great triumph of the bridge builder's skill, and the story of the sinking of the caissons for its piers is so interesting that I purpose to tell it here. The Hawkesbury River Bridge is of the lattice girder type, and has seven spans, each of 416 feet. It is carried at a great height above the river, and seen from a distance appears a very frail and slender structure, which could hardly be expected to carry the great weight of the trains that pass over it. Indeed, one could hardly find a better example of how the bridge designer contrives to combine great strength with great lightness of material. The chief point of interest about the bridge is the bold manner in which the engineers placed the girders in position, and we shall speak of how this was done in the next chapter; just now I want to tell you about the way in which the piers were built. There are, of course, six of these piers, and the foundations for them had to be carried to an enormous depth, this in one case exceeding 160 feet below high-water level. A hundred and sixty feet does not sound a very great depth, and it does not take you very many seconds of time to walk that distance; but if you come to compare it with some perpendicular objects, you will realize what a herculean task it must have been to build a tower higher than, say, three trees of average height put end to end, or your church spire, through mud and water. As a matter of fact, the mud proved a far more serious obstacle than the water, one of the cylinders having to be driven through it for a distance of 120 feet before a bed of rock could be reached.

Now, you will see at once that the engineer could not build a huge steel tube 160 feet in length and many feet in diameter and then sink it, so of course this cylinder could only be made and lowered in sections—as, indeed, are most bridge cylinders. The first thing that was done was to build the bottom section, or shoe, as it is called; and I shall briefly describe the manner in which this was made. Imagine, then, an enormous boiler, with the top end removed, and with three giant tubes running from end to end, the closed end being pierced to admit these, which, of course, have their ends open. Provide the closed end with an arrangement of steel plates shaped to form a cutting edge, turn up the contrivance so that the open end is uppermost, and you will have a good idea, if not a strictly accurate one, of what the shoe of a Hawkesbury Bridge caisson was like. This shoe, of course, was very buoyant, and floated like a barrel in which a weight has been put to keep it upright; and when a little concrete had been put in as ballast it was towed out to its position by tugs and then sunk. This sinking was a gradual process. Liquid concrete was poured in from a ship's hold, so that, as it set, a solid mass was formed around the tubes in the shoe, the tubes themselves being left open to the water. When the shoe had been sunk to water level, another section was built on it, the tubes being carried higher at the same time; then more concrete was poured in, and more plates were added continually as the huge mass sank lower and lower, until at last the shoe rested in the mud, 40 feet below the water, while the tops of the cylinder and of the three tubes were left sticking up above the river.

Perhaps you are wondering about the purpose of the tubes that, as we have seen, led from the bottom of the shoe to the top of the cylinder. The object of providing the tubes, which, you must remember, were not filled with concrete, was to enable the cylinder to be sunk through *120 feet of mud.* Just think of the task of driving this enormous column of concrete encased with steel through 120 feet of mud! The steel cutting edge with which the shoe was fitted was provided to assist in this extraordinary operation, and the tubes were to enable the mud to be got at from above the surface of the water.

When the shoe of the cylinder rested on the bottom of the river, some very queer machines indeed were brought into operation. These were steam grabs, a sort of giant hand which, when lowered down the tubes, seized handfuls of the mud and brought it up to the surface. These machines are almost uncanny



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THE HAWKESBURY RIVER BRIDGE, NEW SOUTH WALES

The bridge has seven spans of 416 feet each. The piers had to be sunk through 40 feet of water and 120 feet of mud before a firm foundation was reached

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in their resemblance to the jaws of some fearful dragon out of a fairy story. The grab consists of two halves hinged together at the top, the jaws being scuttle-shaped, and provided with terrible teeth along their lower edges. It is lowered by a long chain down the tubes of the cylinders, the jaws being open. When the bottom is reached the jaws force themselves deep into the mud by reason of their weight and sharp teeth; then the tightening of the chain as it is wound up causes them to come together, the gigantic teeth closing over several hundredweights of mud and bringing them safely to the surface.

Bit by bit, as the mud was got out, the cylinders sank lower and lower; and all the time, above water, more plates were being added and more concrete poured in, until, after weeks of incessant work, with the grabs going day and night in each of the tubes, the final resting-place was reached. Then the tubes themselves were filled with concrete, and on the tops of the cylinders were built the masonry piers, 40 feet high, that carry the girders of the bridge. This is all that can be seen of the piers; and although, when viewed from the water, they look very solid and imposing, their height represents only a quarter of the total height of the great columns on which the bridge is really supported.

As you can well imagine, the sinking of these cylinders was a work of great anxiety to the engineers in charge. They had to be exactly in the right places, the correctness of which required to be verified by means of elaborate mathematical calculations. You will realize that this was serious enough when I tell you that the girders were being built separately on shore at the same time as the cylinders were sunk, and were placed in their proper positions afterwards; so that if the cylinders had not been in their correct places, the girders could not have fitted on to them, and such an accident would of course have been nothing short of a disaster. But the most difficult part of the sinking of the cylinders was to guide them down in a truly vertical direction, for of course a cylinder being in its right place at the bottom of the river would have been of no use if it had leant over one way or another at the top.

There is never any lack of excitement during the operations of bridge building, and the men who reared the great piers for the Hawkesbury River Bridge had probably a great deal more than they cared about. The shoes for the cylinders were built about a mile away from the bridge, and when completed were towed by a steamer to the positions in which they were sunk. The part played by this steamer and the men who had charge of the business of getting the shoes in place is not the least interesting in the story of the bridge, and it was marked by one very exciting adventure. The shoe, as I have said, may be likened to an enormous and unwieldy barrel floating on its end. Now, a barrel is never a very simple sort of craft to manœuvre, as doubtless you have discovered if you have ever navigated a pond in one. But the Hawkesbury River is hardly as still as a pond—in fact, the tides run with great swiftness, the shores are fringed with rocks, and great gales often blow down the estuary, so that the navigation of the shoes for the cylinders was a very difficult business, and often a hazardous one. Of course, favourable conditions of wind and tide were waited for before the shoes were towed out, but on one occasion a strong wind sprang up after the steamer, with its queer craft in tow, had started on its journey to the site of the bridge. In a short time the steamer found that its charge was becoming unmanageable, and other boats came to its assistance. But their help was without avail. The great cylinder showed an alarmingly adventurous disposition. Perhaps it did not care for the idea of lying for ever more than 160 feet below water and mud; anyhow, it broke away from the boats that were trying to hold it, and careered seawards at the mercy of wind and wave.

The moment was a trying one for the engineers. The great shoe had cost thousands of pounds to build, and the making of it had occupied many weeks. Worse than the loss of money was the loss of time, for the contractors were under an obligation to complete the bridge by a certain date, and every day lost in its building meant that the work of two days had to be done in one. And here was this indispensable shoe, which could only be replaced in a lengthy time, sailing perilously to the open sea, in imminent danger of being dashed to pieces on the rocks! We may be sure that there were bitter words and heavy hearts as the workmen watched the child of their labours being carried, as they thought, beyond hope of recall. Other people might have smilingly wondered how the monstrous shoe would be greeted if it reached the high seas. Would it be taken for a new form of warship? or for a marine gasometer? Certainly it was unlike anything ever before seen afloat, and might well astound the mariner whom it confronted.

Of course the engineers were not idle; the engineer has to think and act as promptly as the soldier, and cannot afford to be idle. Incidents like this are part of his day's work, and he has to know how to deal with them. Telegrams were sent to the port at the mouth of the river, to the effect that if it were in any way possible the monster was to be secured, though there seemed to be but small hope of this, as it was blowing a gale and a high sea was running. However, by a stroke of great good fortune the wind moderated before the shoe had been carried out to sea, and, surrounded by tugs and vessels of all sorts, the runaway was ultimately secured and taken to a safe anchorage. Later on it was brought to its proper place and was sunk in the manner that I have already described; but it came very near to being sunk in the orthodox way, and not as the engineer had intended.

The cylinders of the Hawkesbury Bridge were sunk in the peculiar manner I have told you about on account of the difficulty—one might say the impossibility—of employing any other method. Such cylinders as these are called open-topped, to distinguish them from the pneumatic or compressed-air cylinders I am shortly going to describe. The Hawkesbury cylinders were built entirely from above water, and no men descended, the whole of the excavation of the mud being done by the grabs that worked in the tubes. Open-topped cylinders have often been built in India, where most river bottoms are composed of great depths of sand; and grabs working from the top, as in the Hawkesbury case, have been generally used to clear a way for the cylinders. In India bridge construction is rendered very difficult and dangerous by the sudden and unexpected flooding of the rivers. A bridge is commenced in the dry season, when the bed of the river is simply a great stretch of burning sand, and the danger lies in the flood water coming down and carrying away the bridge works before they have been made strong enough to resist its sudden rush. If you would know what an exciting and terrifying occurrence a flood is for the bridge constructor, you should read a story by Rudyard Kipling called *The Bridge Builders*.

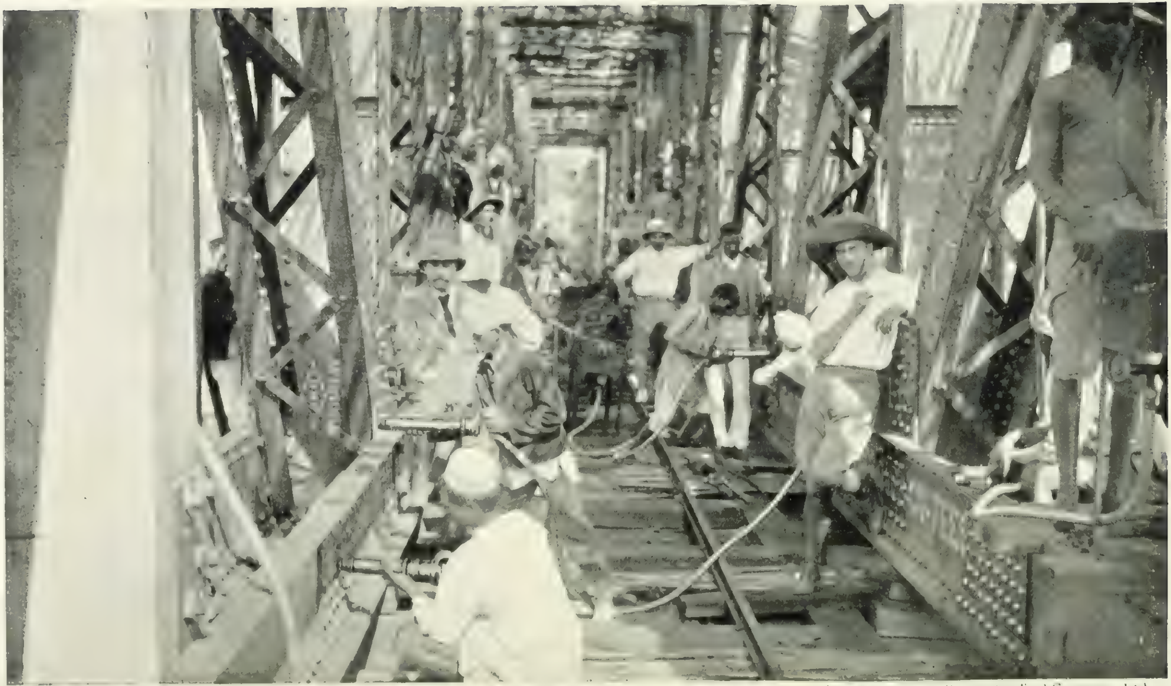
When the river bottom is of stiff clay, open cylinders are sometimes used, and the excavating is done from the bottom by men, instead of from the top by machines. In clay there is not much difficulty in keeping out the water, and when the cylinder has reached the bottom men are sent down and can work in comparative safety. The great cylinders that support the Charing Cross Railway Bridge in London were built in this way, and are carried down some 60 feet into clay.

When the piers of a bridge have to be carried down through sand before a firm resting-place can be reached, the pneumatic caisson is used, provided the depth is not great enough to require so high a pressure of air as to make it unsafe for the men to work. Again, it may be necessary not merely to go through sand or mud to great depths, but to cut or blast away the rock beneath these substances, and in such cases it becomes necessary to employ men at the actual face of the rock. Or the engineer may have to take his foundations through quicksand, or he may meet a spring on the way down, in either of which cases no amount of dredging or pumping will keep out the inflow; the only way in which he then can get the better of these enemies is to keep them out by equalizing the hydrostatic head—in other words, he must employ inside the cylinder a pressure sufficient to overcome that of the water outside the cylinder. In the pneumatic caisson, the compressed air is used to hold back the sand and water that would otherwise be forced into the cylinder from the bottom.

Let us in imagination pay a visit to such a caisson. In the position on which the piers of the bridge are destined to rest eventually the cylinder has been sunk, and we find it surrounded by a great scaffolding of timber. At the top of the shaft is a scene which we might be excused for thinking one of the greatest confusion. There are great balks of timber everywhere, and great steel plates, and puffing steam engines, and noisy cranes. Down the side of the shaft is fixed an iron ladder, and electric lights throw a glint on the cable of a crane, which is hoisting a "skip", or bucket, of "muck", as the navvy calls the product of his spade. Around us and immediately above us riveters are adding more plates to the cylinder, and the clatter of the hammers and the jangle of chains and plates against the sides of the steel shaft make an ear-splitting din. The interior of the shaft glistens with water, and we look downwards into the shadow of the abyss with mixed feelings of awe and wonder. Indeed, the descent of the iron ladder is quite a terrible business, until our nerves become hardened by experience, and we can control our senses sufficiently to disregard the tremendous noise and the whirr of moving cables. We need not be ashamed of the feeling of alarm that is prone to seize us and make our knees tremble as we descend the slender ladder for the first time; it is all very strange and mysterious, and we wonder whether the shaft has not been built by some race of giants to entrap us in the bowels of the earth, while our courage and confidence are not increased by the knowledge that the whole structure—cylinder, cranes, the ladder on which we stand—is moving slowly,

slowly downwards, carrying us surely though imperceptibly nearer to the mysteries of the interior of the earth.

Holding tightly on to the rungs of the ladder and looking down, we see far below us a tiny speck of light. Lower we descend and lower, until the noise overhead becomes fainter, and we are conscious of a new sort of noise coming up to us from the bottom of the shaft: there is the clang of steel doors, the ringing of bells, the shouting of many voices. Looking down again, we find that the speck of light which we saw before has become a glaring electric arc lamp, which sends up to welcome us an ominous buzz. A skip passes us in its ascent, spinning as it goes, and nearly startles us off our ladder; but we are nearly at the bottom, and in a few moments find ourselves standing on a steel floor. We are on the roof of the compressed-air chamber. We dodge on one side, barking our shins against a girder, to escape if we can what looks like certain doom. A skip is coming down with a rush, and as we look up at it we are quite sure that it will crush us, for it seems to fill up the entire shaft. We draw a breath of relief as it comes gently to rest, and we see that there is really room enough for half a dozen such skips and a dozen of ourselves. The bucket empties its cargo in a manner that greatly surprises us. We were prepared to see a load of bricks or steel bars discharged, and instead, through a small door in the side, there crawl one after another ten or a dozen men.



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BRIDGE BUILDING IN INDIA

Pneumatic tools are largely used in bridge construction. In this picture natives are seen closing rivets with Boyer long-stroke riveting hammers.

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These men are going into the caisson to relieve a "shift" that is just going off duty, and we shall be able to go into the airlock with them. We have to wait for a few minutes, and as we look at our rough companions we cannot help wondering whether their hearts are banging with excitement as rapidly as ours. Presumably, however, they are as unconcerned about their surroundings as rabbits in a warren. They are laughing and chatting as they stand about or rest on their tools, armed with pick and shovel, and most of them carrying cans containing their dinners.

We are glad when the suspense is over and a ringing of bells warns us that we can go into the airlock. A steel door opens with a clang, and half a dozen small trucks filled with sand are jerked through the opening. We follow the men through the doorway with sensations very much like those with which we might leave the waiting-room at a dentist's, to be ushered into the consulting room. The door closes behind us, securely imprisoning us in a large chamber. We notice the electric lights and a maze of pipes and electric wires, and hear the hum of a motor and the *tchit-tchit* of an air pump. While we are still looking about and trying to appreciate the multitude of devices that modern science has scattered around us so many feet below the water, we become conscious of a very peculiar and unpleasant sensation in the head, and begin to wish that we were safely on the other side of the airlock. When we went into the lock the pressure that the air exerted all over our bodies, inside us and outside, was normal: but since we came into the lock it has been rising gradually, for compressed air has been pumped in, and the pressure is now 30 pounds to the square inch, or double that to which we are ordinarily subjected. The high pressure gives us a horrible pain in the eyes, there is an awful buzzing in our ears, and very likely our noses begin to bleed. Fortunately, our organs soon adapt themselves to working under the new conditions, and we feel better as a door on the other side of the lock is opened and we pass through. There are more perpendicular ladders to descend, and then we arrive at the working chamber. Yet another door is opened, some laden skips pass out, and we pass in. And now we have come upon a scene of which the like probably exists nowhere else, on the earth or below the waters. We are in a great space, oval or circular, 7 or 8 feet high, and perhaps 50, 60, or 70 feet in diameter. Above us is the basin-shaped roof through which we have come. The electric lights show us the symmetry of the plates and their rows and rows of rivets; so beautifully has the caisson been made that it is difficult to realize that its use is only that of a temporary contrivance, and that as soon as the brawny navvies have done their work the great steel shell will be filled with concrete, and left free to rot, for all the engineers care, at the whims of the salt sea that surrounds it.

But we have not much time to ruminate, nor indeed have we opportunity, for there is a great deal of noise and bustle in this subterranean castle of steel, and the *clink*, *clink* of the workmen's picks reminds us that we are standing on the floor of the river: yes, we are on the floor of the river, or, more properly, of the ocean, for the river is probably a wide estuary.

We are standing on dry land with 40, 50, perhaps 70 feet of water over our heads! Surely there is magic in the methods of the engineer! And the *clink*, *clink* of the picks and the shovels goes on day and night, night and day, until sufficient of the mud or the clay or the sand has been removed; and day and night, all the time, the mighty cylinder sinks lower and lower, until it finds its final resting-place. A shudder comes over us as we think of it; it is rather a terrible thought. Suppose the cylinder should sink too suddenly? There is only a matter of 7 feet between us and the roof of the caisson, and the cylinder weighs between 20,000 and 30,000 tons. Well, a sudden subsidence of the earth beneath a cylinder has happened before now, and embedded in the concrete of the foundations of more than one great bridge are the remains of some of those humble heroes I have spoken about.

Perhaps if we go near enough to the edge of the caisson we may actually witness the water being held up in a wall underneath the cutting edge simply by the pressure of the air in the caisson; and it is a very remarkable experience to put our hands underneath the cutting edge, where it is not supported, and to *feel* the water. There have been occasions when salmon and other fish have actually swum under the edges of caissons, to the intense astonishment of themselves and of the workmen.

But now we must leave the caisson by the way we entered. We climb up into the airlock, which we enter in company with a skipload of "muck", for the doors are not opened oftener than can be avoided, because the air pressure has to be kept constant. It will take us nearly half an hour to be "locked out", for the pressure of the air has to be reduced very slowly, so that we may suffer no harm as the result of our short existence in an atmospheric pressure twice as great as Nature intended us to live in. However, our time need not be wasted, for we can get the man in charge of the great taps that regulate the air valves to explain to us something about the mysterious disease known as "caisson sickness". He will tell us that this strange malady, which nobody quite understands, is one of the chief dangers of compressed-air working. It attacks the workmen in various forms, not when they are in the compressed-air chambers, but after they have come out. They are often seized with agonizing pains in the joints of their legs and arms, and the only thing that will bring relief is for them to return into the high-pressure air. In the early days of pneumatic caissons deaths from this strange "sickness" were of frequent occurrence; nowadays, fortunately, working in compressed air rarely has fatal results, for the men are not allowed to remain in the chamber for more than a few hours, and they are locked out very gradually, as the rapid change of pressure is known to be one of the causes that bring about the dreadful seizures.

Workers in caissons often have very startling experiences. Cases have been known in which the men have dropped their tools and rushed towards the exit from the caisson in a sudden panic as the result of some quite trivial accident, such as is bound to occur now and then. Oftener they have some very good cause for an alarm which, being for the most part brave men, they seldom show. The caisson may suddenly subside and bury them—though such an accident, fortunately, happens very rarely—or owing to one cause or another there may be a sudden and destructive inrush of water. One of the most terrifying experiences the men have to face —and it is one that might well strike fear to the bravest heart—is what is called a "blow". This happens when the pressure on the inside of the caisson becomes greater than that outside. Then the air forces its way past the bottom of the caisson with a mighty roar, filling the chamber with a fine, fog-like spray, and sometimes so reducing the air pressure that the water rushes in. A "blow" causes a remarkable commotion at the surface, a great spout of aerated water being cast up, as though thousands of bottles of soda water had suddenly burst below the surface.

Sometimes the worker in the bridge caisson sees incidents that are amusing as well as startling. The late Sir John Fowler, who was one of the engineers of the Forth Bridge, tells a story of a man who took a brandy flask with him into the working chamber. There he emptied the flask and put it back in his pocket. When he was returning through the lock and the pressure had been reduced, his flask suddenly exploded with a loud report, and the poor man was nearly frightened out of his wits. The inside of the flask was full of air at a pressure of over 30 pounds to the square inch, while the pressure exerted on the outside was only 15 pounds; the glass was unable to withstand the great internal pressure, and was blown to fragments.

You will remember what an exciting time the engineers of the Hawkesbury River Bridge had when the shoe of one of the cylinders got beyond the control of the steamer towing it, and started for a deep-sea cruise on its own account. This accident is only one of a large number that have happened in different parts of the world where bridge cylinders have been sunk, and there is not space here to tell you about them. But in order to show, once again, how careful, courageous, and resourceful the engineer has to be, I will briefly outline the story of one more accident.

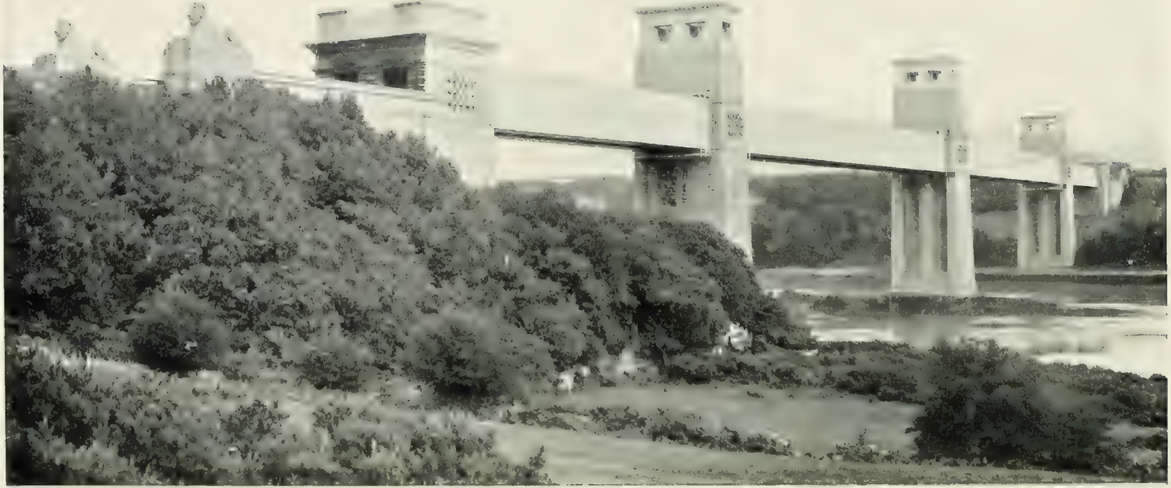
One of the huge caissons that were to help in the construction of the piers for the Forth Bridge—the greatest bridge in design and execution, as well as in size, that the world has yet seen—had been floated into position, and was being loaded with concrete to sink it; but when only 4000 tons had been put in, it suddenly stuck in the mud and canted over. The rising tide poured over its edge, and added to the injury. Of course, it had to be recovered somehow, for, apart from the loss of the thing itself, it was in the position where a pier had to be built, and nothing could be done until the huge sunken mass was removed. Men were sent to add more plates to it, so as to carry the sides above the water level; and when this had been done pumps started to clear it of water. The result of this operation was another accident, more serious even than the first. The great caisson was unable to resist the crushing pressure of the water on the outside when the water inside had been pumped out, and the steel plates were burst inwards as though they had been of paper, two men being killed. It was not until after nine months of arduous labour, during which time divers were at work patching the torn plates, that the caisson was recovered.

CHAPTER III

How a Bridge Grows

We have followed the progress of the building of a bridge from the designer's brain to the erection of the piers. In this chapter we shall see the next process in the giant task, that of the construction of the steel girders that form the bridge proper, and over which the trains will pass. Our best plan will be to take some of the great bridges of which we have all heard, and, assuming the piers to have been built after one of the methods described in the last chapter, to see how the superstructures were put in position.

Let us start with the great Britannia Tubular Bridge, built by Robert Stephenson over the Menai Strait. The bridge takes its name from the Britannia Rock, which rises in the middle of the strait at a point where the water is over 1000 feet wide. It was opened in 1850, and was then considered to be a very great engineering triumph. It had, indeed, the widest span ever attempted up to that time; and although this span has since been surpassed, the Menai Bridge will for many years remain one of the greatest engineering works in the world. It is famous less on account of the great space between



By kind permission of The London, Midland, and Scottish Railway Company

THE BRITANNIA TUBULAR BRIDGE

This bridge carries the London, Midland, and Scottish Railway over the Menai Strait, and was built by Robert Stephenson. The spans are hollow tubes, built up of iron plates.

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the piers—the two middle spans are of 460 feet—than because it introduced a new principle into bridge building, and because of the enormous difficulty of erecting these immense spans.

Before we go any further, let us have a look at the bridge, and gain some idea of how great an undertaking it was. It consists of two continuous tubular beams, each 1511 feet long, and each weighing 4680 tons. One of these tubes is for the up and the other for the down line. They are carried on three piers, or towers, rising from the water; and on smaller land towers, or abutments, built on the shore at each end. The middle tower, built on the Britannia Rock, is 230 feet high, a few feet shorter than the London Monument[1]; it contains 300,000 cubic feet of masonry, and weighs—so we are told—over 20,000 tons. Of the four spans into which the bridge is divided the two in the middle are (as I have already mentioned) each 460 feet long, and those at the ends 230 feet. On the middle towers the tubes rest on special beds provided in the masonry, and on the end towers they lie on roller bearings, so that they may expand and contract with the changes of temperature.

While the masons were at work building the towers, the construction of the gigantic tubes was in progress on shore, more than fifteen hundred men being employed in preparing the boiler plates of which they are made. A tremendously strong staging was built, and on this the tubes eventually arose. Each of the main tubes weighs more than 1500 tons; but as so great a weight does not probably convey very much to your mind, let us attempt to show how big these hollow beams are by a simple comparison. If one of the large tubes were set up on end in St. Paul's Churchyard, the end would be nearly 100 feet higher than the cross on the summit of the cathedral! In the making of the tubes as many as two million rivets were used altogether, about six rivets being required for each foot of plating to be joined. To make these rivets 900 tons of iron bars were used, and if these bars had been joined together in a straight line they would have stretched for a distance of 126 miles, or from London to a place 24 miles beyond Birmingham.

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[1] The Monument is 244 feet high from the base of the column to the top of the vase.

Only the four middle tubes—that is, two for each span—were built on shore, the end tubes being built up on scaffolding in the proper position between the end towers and the abutments. The use of scaffolding was impossible in the case of the middle tubes, because a great timber structure, such as you can imagine to be necessary to support the beams, would have occupied practically the whole space between the towers, and would of course have blocked the way to the shipping passing down the Strait; so these tubes had to be floated into position after they were made, and then raised to their proper height above the river. This was the great problem of the Menai Bridge.

When a tube had been completed the staging was cut away from under it in places, and a big basin or dock, open to the sea, was dug out beneath it. There were then constructed four large pontoons, which were placed in position under the tube; in these there were valves, by means of which the water could flow into and sink them. When all was ready for moving a tube, the valves were closed and the water was pumped out, and as the pontoons floated they lifted the immense mass of steel off its supports, and bore it upon the waters of the Strait. All this was easy enough: the great difficulty lay in the task of floating the tube out to its position between the towers. For this operation the services of an enormous number of people were requisitioned, and on both sides of the Strait great crowds assembled to witness the proceedings. The pontoons and their freight were harnessed to steamers by hawsers 12 inches thick; other hawsers were attached to capstans fixed on shore; and when all was ready, the last tie holding the pontoons to the shore was cut, and off they floated with their 1500-ton burden, "like a mountain moving on the waves", as one writer put it.

At the first attempt the tube did not get very far on its voyage. One of the capstans gave way under the strain, and the floating monster was brought back and "anchored". However, the next attempt was successful, though not without sensational incidents for engineers and spectators—the latter finding themselves called upon to help with their hands, as well as with their voices. The tide was running strongly, and as the pontoons neared the piers they moved with a fearful speed. At the critical moment an accident happened that very nearly put a sudden and disastrous end to the whole proceedings. Owing to the fouling of the rope, one of the shore capstans jammed, and, being unable to resist the onward motion of the pontoons, was bodily pulled from its foundations. The men working it were knocked down and hurled into the water. The pontoons were in imminent danger of being carried away by the stream or smashed to pieces on the rocks, but the tube was saved from its perilous situation by the presence of mind of the man in charge of the broken-down capstan. He called upon the spectators on shore to come to his aid, and handed out to them one of the great 12-inch cables. A crowd of men, women, and children bore upon the unwieldy rope and carried it up a field, and by the timely help of these people the progress of the tube was arrested, and it was brought safely into its proper position.

You must understand that at this stage the tube was not many feet above the water. Special ledges had been built on the piers to receive it, and when the pontoons had been guided into the right place, the ends of the tube were secured by means of enormous chains, so that they hung directly over the ledges prepared for them. Then the pontoons were scuttled, and as they slowly sank they carried the tube down with them until it rested on these ledges, leaving the pontoons free to be drawn away from underneath. So beautifully had piers and tube been made that when they were in position it was found that there was no more than three-quarters of an inch to spare between the ends of the tube and the masonry—that is, a seven-thousand-three-hundred-and-sixtieth part of the length of the tube.

The next operation was to raise the tube up to its final height above the water. To do this, a hydraulic press was erected in the Britannia tower. Engines developing eighty horse-power were set to work to pump the water required for raising the ram of the press, which had a lifting power of 2600 tons. At the top of the ram was fitted an iron beam, from which hung chains weighing 50 tons; and to these chains the ends of the tube were attached. Thus the tube was raised a few feet at a time, the masonry being built up under it after every lift.

When the tube had been lifted up about 24 feet an extraordinary accident occurred, which nearly undid what it had taken the engineers many months to accomplish. We cannot do better than repeat Robert Stephenson's own account of how this accident happened:—"One day, while the hydraulic presses were at work, the bottom of one of them burst clean away! The crosshead and the chains, weighing more than 50 tons, descended with a fearful crash upon the press, and the tube itself fell down upon the packing beneath. Though the fall of the tube was not more than 9 inches, it crunched solid castings, weighing tons, as if they had been nuts. The tube itself was slightly strained and deflected, though it still remained sufficiently serviceable. But it was a tremendous test to which it was put, for a weight of upwards of 1500 tons falling even a few inches must be admitted to be a very serious matter!"

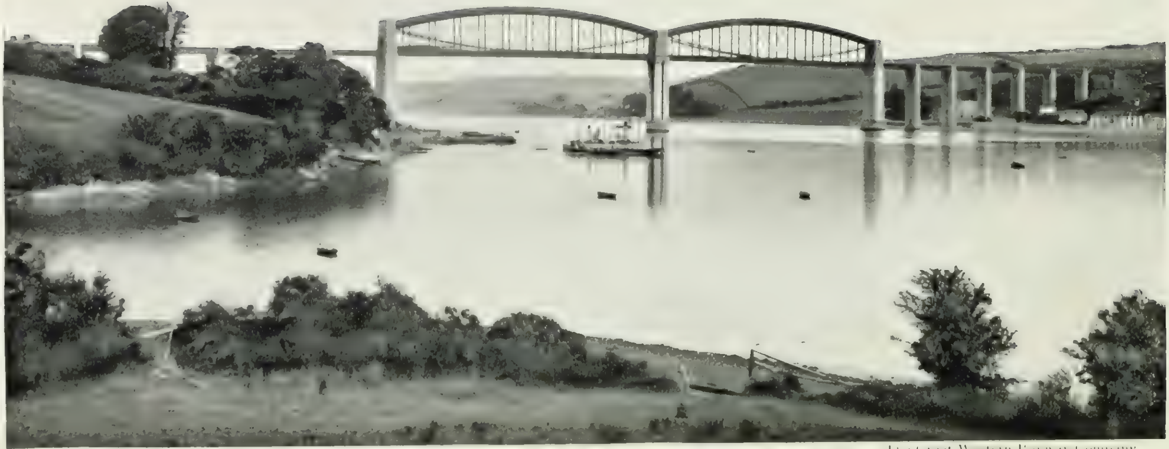
The accident caused an extra expense of £5000, and a considerable delay in the progress of the building of the bridge. One after another the three remaining tubes of the middle spans were floated into their positions, and raised up into the towers, in the manner already described, and nothing further untoward happened to mar the completion of the bridge, which was opened for public traffic in March, 1850. It had cost £234,450, and had taken over four years to build. At the time of its construction it was regarded, not merely as a triumph of engineering, but as the greatest work ever executed in iron and stone.

Robert Stephenson was one of the world's greatest engineers, and his tubular bridge over the Menai Strait—a mighty iron arm thrown across the sea—is a monument to his genius and perseverance. But it is more than that; for we must not forget that without the men who forged the plates and riveted them into the tubes, and who built the masonry and manned the capstans, the bridge could never have been made: let us therefore call it a monument in honour and praise of the industry and skill of the British workman. And, apart from the engineer who designed the bridge, who conceived it and built it first in imagination and then on paper, and the army of workmen who took the paper and copied the bridge in iron and stone, there is one man who is not often remembered, but whose share in the building of the bridge was as important as any. This was William Fairbairn, engineer and mathematician, whose experiments decided the shape and size of the tubes.

If you will look at your map of England, you will see that just to the west of Plymouth there is a break in the coast line, and that the sea, running inland, forms a wide, land-locked bay. This is, in fact, Plymouth Sound, and is formed by the magnificent river Tamar, which separates the county of Cornwall from the county of Devonshire. When the Cornwall section of the Great Western Railway was being built, it was necessary to cross the Tamar, and a spot was chosen opposite a little place called Saltash as being the most suitable for the building of a bridge. The Saltash Bridge is one of the finest in the world, and is the work of the great engineer, Isambard Kingdom Brunel. It has a total length of 2240 feet—nearly half a mile—divided into nineteen spans; the two middle spans are of 455 feet, the remaining seventeen being comparatively short.

The foundation for its middle pier had to be carried down to a great depth, pneumatic caissons being used for this purpose. The first cylinder was sunk in 1854—four years after the completion of the Menai Bridge—and the work on shore and under water went on unceasingly for five years, the bridge being opened in 1859. On the masonry of the middle pier there were built up four great cast-iron columns to support the middle spans. These columns are no less than 100 feet high and 10 feet in diameter. They were cast in sections, their surfaces where they are joined being planed as accurately as though they were parts of a watch. The great middle spans are, as you can see from the picture, very graceful and light in appearance. They represent a combination of an arch and a suspension bridge, the arches being above the railway, and made of iron plates riveted together to form an oval tube. The suspension chains are very massive, in spite of their slender appearance, and are made up of fourteen iron "links", placed side by side, and connected together at intervals throughout their lengths. Each of these links or iron bars is 1 inch thick and 6 inches deep. From the top of the arched tubes to the bottom of the longitudinal girders that are suspended from the chains, and carry the railway lines, is a distance of 56 feet; while from the summit of the bridge to the submarine foundation is a distance of 260 feet; so that if the London Monument — to recall an old friend with which we have made a comparison before—were set up on a level with the foundations, the bridge would rise 16 feet above it!

The middle spans were built on shore, as in the case of the Menai Bridge, and were then towed out on pontoons and raised to their great height above the water by means of hydraulic presses, in a manner very much the same as that adopted by Robert Ste-



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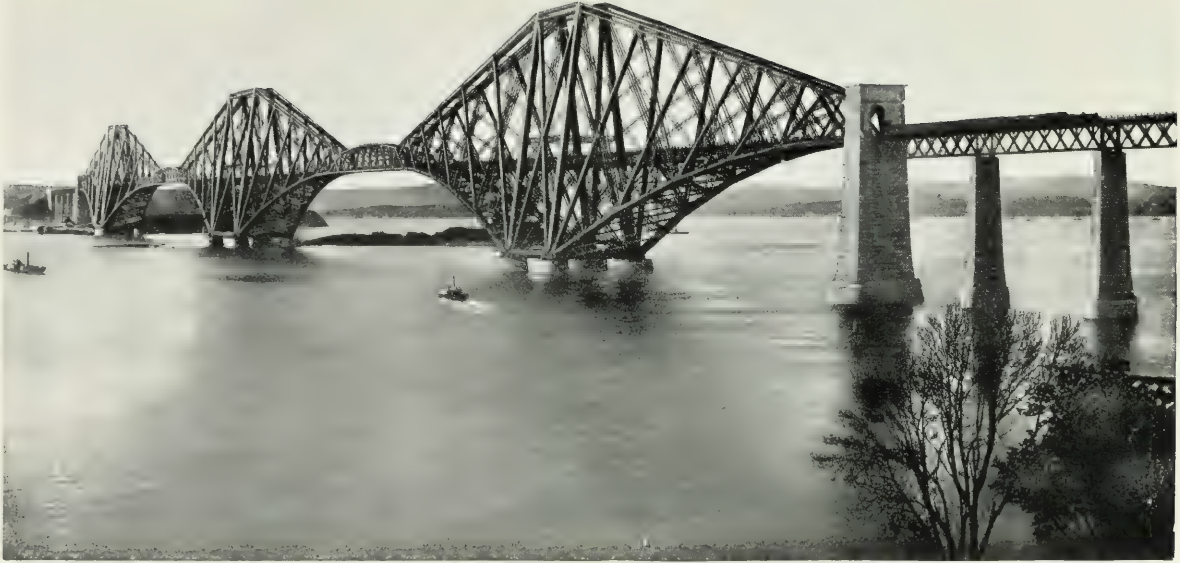
THE SALTASH VIADUCT

This beautiful bridge was built by Brunel across the River Tamar in Devonshire. The middle spans are 455 feet. *Page* [illegible]



Photo, Valentine

THE FORTH BRIDGE, THE LARGEST IN THE WORLD

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phenson. They were raised up only a few feet at a time, the masonry of the landward piers and the cast-iron columns on the middle pier being built up under them bit by bit.

In the last chapter we dealt with the sinking of the cylinders for the piers of the Hawkesbury River Bridge in New South Wales, and now we will return to this bridge, because it serves as a good example of the difficulties of floating out bridge girders. In the Menai and Saltash bridges the spans were floated out before the piers were completed — in fact, when they were only a few feet above water level. A more daring operation was involved in the floating of the spans for the Hawkesbury Bridge, for in this case the piers had been built to their final height, 40 feet above high water. The seven spans of the bridge were built up on a scaffolding of timber, which was the same height above the water as the top of the bridge piers, and was carried on an immense pontoon a little less in size than the space between the piers. Mr. C. O. Burge, who, as resident engineer, was in charge of the building of the bridge, gives us an exciting account of an adventure that befell one of the spans, in a book in which he has recorded his experiences as an engineer in many parts of the world. Mr. Burge says: "Perhaps the most exciting of all the many contingencies which occurred during the construction of the bridge was the adventure on the voyage of the span at the south end of the bridge. The site was, of course, close to the shore, and quite near to the latter were many sunken rocks. The pontoon with its load was successfully navigated to near the site, and all was going merrily as a wedding bell, when great delay occurred in trying to warp her round. The hitherto rising tide had begun to turn, and before the manœuvre was complete one end of the pontoon got aground on a sunken rock, the rest of it being in deep water. For many hours all efforts to draw her off failed—efforts stimulated by the possible serious consequences of failing to do so, for with the tide still falling the floating end would gradually sink more and more, the other end remaining stationary; and unless the slope at low tide was still insufficient to cause it, the great girders of 1000 tons weight would slip off into the deep river. In such case they would be utterly lost, not only by smashing themselves to pieces, but by being sunk in 100 feet of mud, and nothing that could be done would have held them back. Moreover, if the whole vessel with its load had slipped off, destruction would equally have occurred, as the top-heavy character of the loading was only suitable for quiet movement, and not for the violent plunge downwards into the water which this result would have caused. The loss in a moment of time would have been enormous, besides causing serious delay in the opening of the bridge. The engineers and contractors' representatives stood by on shore absolutely helpless, only trusting in the possibility of the tide turning before the steepness of the inclination of the girders would have been too much for their stability. Their hearts almost stood still as the time for low tide indicated by the almanac approached. The situation seemed desperate; great creaks and groans were heard, as if the mighty structure was straining all its muscles, so to speak, to save itself, when, just as it was thought that all was over, the witching time of low tide arrived, the crisis was passed, and the girders held fast. A few inches less of water, and the newspaper posters of the world would have been blazoned with the disaster. As the tide rose, the pontoon again lifted itself level, and when high water occurred she was afloat end to end, and was safely brought into position."

In the preceding chapters mention has been made of the Forth Bridge; and we will now see how this, the greatest of all bridges, was built. Before we go any further, however, let us have a look at this bridge, for the purpose of gaining some idea of its immense size. Some of you doubtless have seen the bridge in reality, and you cannot have failed to be impressed by the towering structure of steel stretching across the beautiful Firth of Forth. If you have thought for a moment of whence it came, and what it is made of—of the shapeless, dull-brown iron ore and the mysterious substance in the heads of men that we call brain—then, surely, you must have felt how wonderful a thing the Forth Bridge is, and how wonderful is the state of civilization that enables men not merely to build so colossal a structure, but to be willing to spend more than three and a quarter million pounds, in order that passengers and merchandise may, without danger or delay, cross a strip of water not much more than a mile wide.

The total length of the Forth Bridge is a mile and a half. It consists of two spans, each of 1710 feet; two—the shoreward ends of the cantilevers—of 675 feet; and fifteen spans of 168 feet, forming the approaches to the bridge. The great cantilevers between them, and including the piers, cover a distance of a mile. The weight of one of the great spans is about 16,000 tons, and the weight on the tower foundations is 25,000 tons. A large number of other figures could be quoted, with a view to showing how enormous the bridge is, and how very much bigger it is than other bridges; but, after all, figures do not help very much, unless we have something tangible with which to compare them. When our geography books tell us that Mount Everest is some 27,000 feet high, we are not very much the wiser. But when we enter a mountainous district for the first time, mountains which are really quite small seem to overawe us by their size; and if we gaze on Ben Nevis, with its snowy crest 4406 feet above the sea level, and mentally compare it with Mont Blanc, which is three and a half times as high, we have some conception of Mont Blanc's vast height; and, continuing the comparison, Mount Everest's 27,000 feet begin to have a significance for us that no geography book could ever give. And so it is with all big things, be they worlds, or mountains, or bridges. A mile is a good distance—especially when we are walking quickly, and are afraid we shall not catch our train—and it is a very familiar distance; yet it is not at all easy to conceive a bridge spanning a mile of water with only two intermediate supports, so we must look for something more tangible with which to make a mental comparison.

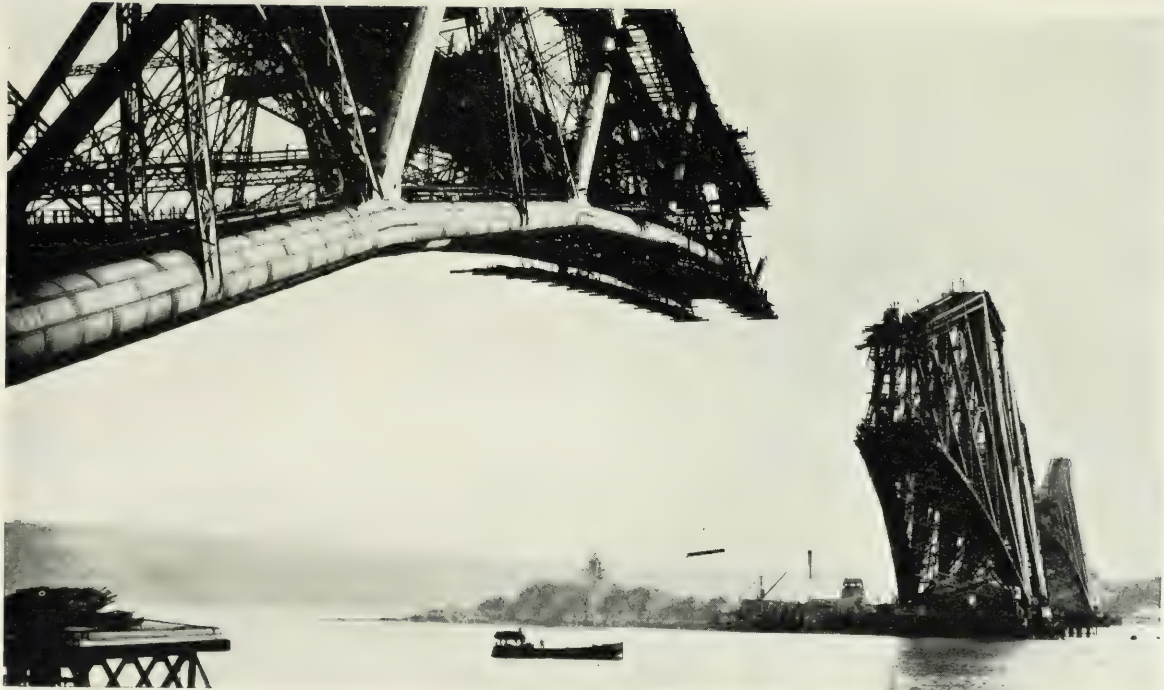
What about the Menai Bridge? That, we know, is an enormous bridge, and it is a suitable object for comparison with the Forth Bridge. Instead of telling you how much larger than the Menai Bridge the Forth Bridge is (you can find that out for yourself easily enough), I propose to use a comparison that was made at the time the Forth Bridge was opened, when the whole world, scientific and unscientific, looked agape on the mammoth structure. As the Menai Bridge is to a new-born babe, so is the Forth Bridge to a Life Guardsman; in other words, the difference in size between a baby and a Guardsman is proportionately the same as the difference between the Menai Bridge and the Forth Bridge. We might carry our comparisons much further; but I shall only quote one more, which is specially interesting as showing how Robert Stephenson could never have built the Forth Bridge with the material of which the Menai Bridge was constructed. The Menai Bridge, you will remember, is built of iron plates, and these have a tensile strength of 22 tons per square inch. In the interval between the completion of the wonderful structure spanning the Menai Strait and the commencement of the still more wonderful structure spanning the Firth of Forth, processes of manufacturing steel in commercial quantities had been introduced, and it was the coming of steel that made the Forth Bridge's great cantilevers possible. Without steel, which has a tensile strength of 10 pounds to the square inch more than iron, the most ingenious engineer in the world could not have carried out such a huge span. Sir John Fowler, one of the engineers of the Forth Bridge—Sir Benjamin Baker being the other—says that Robert Stephenson calculated that, with the iron used in his Menai Bridge, a bridge of the span of 1710 feet might be constructed; but not an ounce of weight must be put upon it, nor a breath of wind allowed to blow against it. The great spans of the Forth Bridge are, as has been mentioned, 1710 feet, and when tested by the Board of Trade inspectors, 1830 tons were put upon the 1710 feet; but 4000 tons might have been put on the spans without injuriously affecting the structure.

The bridge was commenced in 1883, and was finished in 1890. During its construction an army of nearly 4000 men was employed on the bridge works. Reduce this number to one man, and you will find that if he had started 28,000 years ago, and had worked day and night continuously ever since, with all the materials, appliances, and machinery necessary to help him, the machines being capable of doing their work without his attention, the bridge would just be finished; and it would just be finished if, say, thirty-five men, equally well equipped, had started in the year 1112, when King Henry the First occupied the throne.

In Chapter I, p. 22, the principle of the Forth Bridge was fully explained to you, and in the last chapter we went deep—in a literal sense—into the foundations of the bridge; so we need only mention here that the "sky-scraping" towers from which the cantilevers spring are each founded on four submarine piers of granite and concrete. There are thus twelve piers in all, the deepest being nearly 90 feet below high water. The steel towers themselves are 330 feet above the masonry piers, which were built up 18 feet above the water. The total height of the bridge, measuring from the summit of the tower to the rock on which the lowest pier rests, is 437 feet. Not many of us, I think, would care to climb like a human spider up this gigantic web of steel, and look down on the waves 348 feet below us; yet the men who built the bridge had to do this, and did it as unconcernedly as the fly walks across the ceiling.

When the masonry piers had been built to their full height, great bolts were fastened to them for carrying the bed plates of the "skewbacks", as the horizontal steel tubes that spring from the piers are called, to which the lower booms of the cantilevers and the great vertical tubes of the towers are connected. Before any of the steelwork could be built, it had, of course, to be made. The preparation of the material was in itself a task of great magnitude. On the shore near the bridge an enormous ironworks arose. As you can see from the pictures, the principal members of the cantilevers are tubular, and as soon as the steel plates arrived they were passed to the rolling mills, where 800-ton hydraulic presses rolled them to the correct thickness, shape, and size. Then the rivet holes were correctly drilled in them by means of hydraulic drilling machines, and after the edges of the plates had been accurately planed, great cranes took them in hand, and they were temporarily put together on shore. Special hydraulic machinery had been devised for dealing with them, and day and night multiple drills tore their way through the tough metal. It was calculated at the time that the drills performed work which was equivalent to boring an inch hole through a 280-feet thickness of solid steel every twenty-four hours. The tubes thus built up of the plates were 12 feet in diameter, that is, slightly larger than the tunnel of a tube railway.

The vertical tubes of the towers are 343 feet high, and had to be built very carefully indeed in order that they might be perfectly straight. Every now and then they were tested to ensure that they were perfectly vertical, and if there was found to be any error, it had to be corrected in a very extraordinary way. These giant tubes had to be *bent straight*, or, as that seems to contradict itself, let us say *pushed straight*, with hydraulic rams. Does it not give us



By kind permission of Mr John Murray

THE FORTH BRIDGE IN COURSE OF CONSTRUCTION

The great tubular girders, or "skewbacks", forming the lower booms of the cantilevers are almost as large in diameter as a tube railway.

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a newer and clearer idea of the power of water, at once the most docile and the most irresistible of forces, to read that these twelve cylinders, strong enough to bear a strain of some 6000 or 7000 tons, were pushed into their desired positions as easily as you could bend a piece of wire?

But we are going ahead too fast, for we have not yet explained how the tubes were put into position in the first place. The method of constructing the Forth Bridge was quite different from that followed in the cases of the bridges that have already been described. Scaffolding was out of the question, owing to the depth of the water and the exposed position. As your wits will tell you in an instant, it was impossible from the nature of the bridge to build the girders on shore, and then tow them into position and lift them up: for in the case of the Forth Bridge the girders are part and parcel of the towers; in other words, the steel towers are part and parcel of the cantilevers. The method adopted, therefore, was to build first the superstructure, or part of it, on the piers—that is, the steel towers—and then to build out the cantilevers, piece by piece, on either side, so that while the work on the right-hand side of a tower grew in size and shape, equal progress was made on the left-hand side.

The skewbacks (see p. 79) having been fixed to the bed plates on the masonry piers, the horizontal tubes and the vertical tubes were built up and out as far as steam cranes could reach. Then a lifting stage, consisting of two platforms, one on each side of the bridge, was erected. To lift the stage four hydraulic rams were arranged in the 12-foot tubes, cross girders, supported on temporary steel piers, being placed in the tubes to take up the thrust of the rams. The platforms carried travelling cranes, riveting cages, and workmen, and with their cargo were lifted up 16 feet at a time, the plates being riveted in position, of course, before and after each lift. The riveting cages were covered with wire netting, to prevent rivets falling on the men below; and when they were swung high up in the air, the diminutive-looking crane perched above them, they must have looked not unlike real bird cages.

As the towers grew higher and higher, the workmen seemed to grow bolder and bolder, so that they would trust themselves to slender planks, ropes, and girders at a height of 350 feet, apparently unconscious of danger. It is not surprising to read, therefore, that there were a terrible number of accidents during the building of the bridge, although elaborate safety appliances were provided by the engineers. Sir Benjamin Baker himself said the greatest danger to the workmen was the men's own rashness. Writing at the time of the building of the bridge, he said: "A man going up in a hoist the other day, having that familiarity with danger that breeds contempt, did not trouble to close the rail, and stumbling backwards fell a distance of 180 feet, carrying away a dozen rungs of a ladder with which he came in contact, as if they had been straws. But men run risks from their fellow-workmen. Thus a splendid fellow, active as a cat, who would run hand over hand along a rope at any height, was knocked over by a man dropping a wedge on him from above, and killed by a fall of between 100 and 200 feet. There are about 500 men at work on each main pier, and something is always dropping from aloft. I saw a hole 1 inch in diameter made through the 4-inch timber of the staging by a spanner which fell about 300 feet, and took off a man's cap in its course. On another occasion a dropped spanner entered a man's waistcoat, and came out at his ankle, tearing away the whole of his clothes, but not injuring the man himself in any way." Altogether, during the building of the bridge more than 50 men were killed, and more than twice that number seriously injured. Many of us, who have nothing to do with bridge building, but are rather careless of the safety of others, might well take a lesson from that terrible casualty list, and the preventable causes that made it so heavy.

The girder in the middle of each 1710-foot span is not, strictly speaking, part of the cantilevers, but is what is known as a suspended girder. It is 350 feet long, and rests on expansion bearings on the ends of the cantilevers, so that it is free to contract or expand with changes of temperature independently of the rest of the bridge. You will understand that unless provision were made for this, a very serious strain would be set up in the vast mass of steel, which might have disastrous effects. As it is, the bridge girders are free to move 18 inches, a good deal more than the hottest day or the coldest night ever requires.

The joining of the middle girders was the crowning feat of the whole construction, and virtually completed the bridge. So great was the height at which these girders met above the water, and so swift are the waters of the Forth, that it was not possible to build the girders and then hoist them up, so that they had to be built up as though they were parts of the cantilevers, the ties and rivets connecting them to the cantilevers being merely temporary, and called on this account "falsework". The middle girders were thus built out simultaneously from the ends, on the overhanging system. A crane was moved to the end of the girders every time a new length was riveted up, and was thus always in position for handling the fresh plates as they were brought up. At length there only remained to put in the last lengths, or key-pieces, in order to close the gap in the middle girder, and so to complete the bridge. Both top and bottom booms of the girders had to be joined, of course, and this was done at night, when sudden changes of temperature were unlikely to disturb the operations of the engineers. As a matter of fact, a change of temperature had a very startling effect on one of the girders—so startling that at first it was feared that there had been a disaster. This is what happened. The key-plate connecting the ends of the girders had been driven in, and some of the bolts in the middle joints of the connecting ties had been severed, with a view to freeing the girder from the cantilever, when the workmen were startled by a report like a shot from a heavy gun, and a concussion which shook the bridge from end to end. When the confusion was over, the middle girder was found to be swinging on its rockers as easily as if it had been freed in the most natural manner, as indeed it had; for the rise in temperature having put too great a strain on the rivets remaining in the falsework, the rivets had sheared or broken off, thus saving the men the trouble of cutting them out.

We may pass now to the building of a very different type of bridge, in a very different part of the world. In imagination we have gone to South Africa, and have accomplished the railway journey from Cape Town to Bulawayo, the capital of Matabeleland. We have travelled 1360 miles in a most luxurious train, with dining and sleeping cars and every comfort and convenience that the heart of the traveller can desire. From Bulawayo we pass on, still in the train, towards the heart of equatorial Africa, until, a little under 350 miles from the capital, we arrive at one of the great waterfalls of the world, and one of the engineering conquests of the world. The waterfall is, of course, that known as the Victoria Falls, on the Zambesi River; and the engineering triumph is the bridge that has been thrown across the falls by the promoters of the Cape to Cairo Railway—the most wonderful link in that wonderful chain of communication through Africa.

The height of Victoria Falls is 400 feet, two and a half times the height of Niagara; the width is 1 mile, or twice the width of Niagara. The bridge has been thrown across the gorge a little below the falls. It consists of a huge steel arch with a span of 500 feet, the rails being 400 feet—a good bit higher than St. Paul's Cathedral, or the great towers of the Forth Bridge—above the water level.

In this case centering, or scaffolding for erecting the bridge, was obviously out of the question, and it could only be built on the cantilever principle, each end being built out, piece by piece, until the two halves met in the middle. The first difficulty was to establish some means of communication across the chasm by which men and materials could be got from one bank to the other. The distance across the gorge is some 700 or 800 feet, while the only means of reaching the opposite side was to go round, by land and river, a distance of about 9 miles. The engineers, therefore, constructed a cableway. First of all they fired rockets, to which were attached fine string, and after several fruitless attempts a string was carried across. By means of the string a cord could be pulled across, then a wire, and finally a stout steel cable. Running on the cable, and worked by an endless wire, was a cage in which men and materials were afterwards hauled across. Sir Douglas Fox & Partners were the engineers for the bridge, the Cleveland Bridge Company of Darlington being the contractors. Mr. Francis Fox's son was the first to cross the gorge by the wire rope, and he gives a graphic account of his sensations during this novel voyage. He says: "As they tied me into the 'bosun's chair' I must admit feeling a bit strange in relying absolutely on my own calculations for my safety. The chair is a piece of wood suspended by four ropes, with a canvas back, and a sack and board as a foot-rest. Of course one is so tied in that, were you to lose consciousness, you could not fall out; this precaution, for some people, is advisable. All ready, so they gave the signal to the windlass on the south side, and I felt the endless rope tightening and pulling up the stock, and slowly out the pulley ran. The precipice is so steep on the north side that after 5 yards of one's journey you are hanging over a 100-foot depth, and after 30 yards over the rushing water 400 feet below—more than the height of St. Paul's Cathedral. It was a novel experience, and one well worth feeling, as the eye finds it so difficult to give a correct impression of the height—the stereoscopic effect is not great enough in looking downvards (a most unusual direction); but as the 'boys' working at the bridge hurled down huge boulders and stones, I then noticed that the long time taken for these to reach the water below me was much more startling than when seen from the opposite side. No downward motion can be discerned, only the dwindling of the rock in size, due to the perspective effect, as it falls lower and lower, before reaching the water with a report like blasting and a splash more than 50 feet in height. I found myself quite relieved when directly over the water, with no prospect of falling on to a rock in the event of the rope breaking. After the first few moments there is a real charm in looking down; nothing but space between you and the water, save for the 'sag' of the returning endless wire. Of course the predominant thought is, what would one feel if the pulley broke; whether you would really be unconscious after the first hundred feet; whether that last jerk you felt isn't the cable snapping; and you hurriedly looked down to see if the water and rocks are not rushing up to meet you in your downward flight, and are relieved to see the cable still intact, and stretching in a graceful curve to either side of the gorge."

I think that enough has been said to show that the science of bridge building is a very wonderful one indeed, and that the erection of a big bridge calls for as much ingenuity and resourcefulness on the part of the engineer as does its design. It would be difficult indeed to point to any two important bridges that have been built in exactly the same way; there is sure to be some difference even when none appears on the surface: and if we were to go on describing familiar bridges and the stories of their building, this book would contain nothing about those conquests in other branches of engineering of which I want to tell you. So that we must shortly take leave of the bridge builder and his works, those monsters of inanimate steel and stone that cost so much in money and in men's lives, so much care and

thought and anxiety, that, though we may only whisper this, broken hearts and broken fortunes, yea, even shattered minds, are sometimes the reward of those who strive, as we have seen, to harness the earth with reins of steel. Let us hope that after what we have learnt—and the more we know of the inner meaning of these colossal structures, the more ignorant we are apt to find ourselves—we shall regard them, not with a complacence that borders on indifference, but in the light of the wonders of science, by which men are striving, however indirectly, towards the betterment of their kind—a light which we sometimes call by another name, spelt *p-r-o-g-r-e-s-s*.

Well, well! Perhaps I had better not close this chapter, and condemn our bridges to so sudden a dismissal, just yet. For if I do, you may be sure that the critical gentlemen whose business it is to say unkind things about books which they have not written; who sleep all day, coming out, like literary owls, to feed at night, and to pounce with fiercest claws on any small mice in the way of books which may be good for the price of a meal, will make a meal of me. I have not told you all I ought to have told you about bridge building, and the critical gentlemen know it.

We have seen bridges that were built on shore and then towed away and raised up between their piers, and others that were built up piece by piece. And are there other ways? Of course there are—hundreds of them! One of the commonest methods, when the spans are not very big, is that which consists in rolling forward each new girder as the one behind it is completed. The first girder is built on shore, and is then launched forward on rollers until it rests on the abutments at one end and the first pier at the other end. Then the next span is built on top of this, and is rolled forward in like manner between the first and second piers. Sometimes a huge timber scaffolding, known as a traveller, is employed. This is a popular method with American engineers, for it enables the work to be carried on with great speed. When one span of a bridge is completed the traveller is erected on it. Sometimes this traveller may weigh 100 tons or more, and it stretches out for a great distance in front of the bridge works. In the front of the traveller are cranes and derricks, which pick up the girder for the span in advance of it and haul it into position. Owing to its great height, the steel towers that spring from the masonry piers of many bridges can sometimes be constructed with greater rapidity and less danger by the help of the traveller than by any other method.

One of the greatest difficulties with which the bridge engineer can be confronted—and we have seen that his work is seldom free from difficulties — is the alteration of existing bridges, or the substitution of new bridges for old. As you may well imagine, when an old bridge carrying a railway has to be replaced by a new one, the question of what is to be done with the trains while the one bridge is taken down and the other put in its place is a very serious one indeed. On many lines of railway the stopping of the trains for any length of time would be little short of a catastrophe, and it often happens that the engineers have only a few hours in the night-time in which to carry out their operations. In such cases everything is got ready beforehand; the old bridge is moved to one side, girder by girder, and the new one built beside it, until at last, with hardly an apparent interval, the new occupies the place of the old. So expeditiously and carefully is this work done that train A will pass over the old bridge at, say, midnight. An hour later train B will pass partly over the old bridge and partly over the new one, the right-hand wheels on the old girders and the left-hand on the new; while yet an hour later train C may pass entirely over the new bridge. Then the old bridge has carried its last load, and is no longer a bridge, but a mass of scrap iron.

So far the bridges which have been described have been fixed bridges; but there are many forms of movable bridges, and we must spend a minute or two in company with these before saying good-bye to the bridges altogether. One of the earliest forms of movable bridge was the pontoon, an object which will immediately associate itself in your mind with the Latin *ponts*. Pontoon bridges are still in use on the broad and sluggish rivers of the eastern counties of England, and are really floating bridges, the gangways at the ends being capable of movement up or down. One of the most curious of these pontoon bridges is that across the Volga at Nizhn. Novgorod.

In many parts of the world where there are wide stretches of water and much traffic, such as river estuaries and harbours, and where an ordinary fixed bridge supported on piers would interfere with the passage of ships, what are called "flying" bridges have long been in use. Strictly speaking, these are not bridges at all, but steam ferries, which, when loaded with people, horses and carts, and even railway trains, are hauled across the water on cables. But there is a type of bridge, of quite modern origin, which is arranged on a very similar principle, but with this important difference, that the platform on which the water is crossed is suspended above the water. Such bridges as these are called transporter bridges, and there are several examples in England. One crosses the river Mersey, between Runcorn and Widnes; another the river Usk at Newport, in Monmouthshire; and a third, spanning the Tees between Middlesbrough and Stockton, was opened in October, 1911. Such bridges as these are very interesting. On either side of the water there is erected a high tower of steel lattice work, and the towers themselves are connected at the top by slender-looking girders, which project beyond them on either side. Hanging from these girders by means of cables is a cage, in which the freight, human and otherwise, is taken across by electricity. The bridge from which this is suspended is high enough above the water to allow tall-masted ships to pass along without interruption, and it is probable that many transporter bridges will be built in the future. At present these are only available for road traffic. This is not due to want of strength in such bridges, though they certainly look light and almost flimsy; for, as a matter of fact, they are very strong, and capable of carrying great weights, being made as slim as possible in order to economize material, and to offer little resistance to the wind. The reason why they are not used as railway bridges is that they necessarily afford a break in the continuity of a line, and it is inconvenient for a train to have to stop in order to be taken on and off a suspended car.

When a railway has to cross a waterway which is used for shipping, swing or bascule bridges are generally used, as then the passage of the boats need not be interrupted. The Tower Bridge is a bascule bridge; a swing bridge is one that turns round on a central pivot to allow ships to pass by it. The lifting of the bascules, or the turning of a swing bridge, is generally accomplished by hydraulic power, and elaborate safety appliances are provided to ensure that, if anything goes wrong, the movable part of the bridge cannot get out of hand, or move more than a certain distance.

CHAPTER IV

The Making of the Tower Bridge

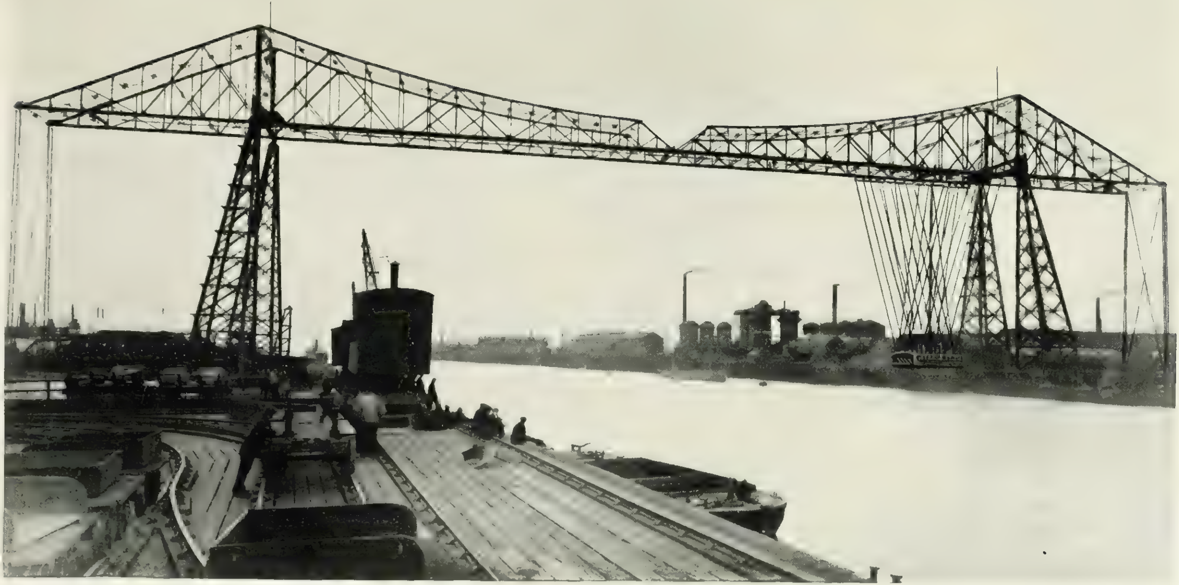
Of course all my readers have heard of the great Tower Bridge, and many, doubtless, have seen it—have probably passed over it or under it. But if they were asked why and how it was built, and how it works, it is quite likely that there would be an unedifying exhibition of ignorance; for the Tower Bridge, like many other great works of man and Nature, is so familiar and so well known that few of us ever take the trouble to improve our acquaintance with it.

It is not the biggest bridge in the world, although it is the largest bascule bridge. I shall not say whether or not it is the handsomest bridge, for the simple reason that I do not know, though I do know that many people, well qualified to judge, say that it is very beautiful, and that other people—equally well qualified to judge—contend that it is very ugly. Both sides appear to be quite happy in their opinions, and it would be a pity to disillusion either of them. Whether it is big, or beautiful, or useful, matters not here, but I am going to ask you to bear with me through this chapter, because the

Tower Bridge of London is one of the famous works of the capital of the most famous empire; and because a book about engineering conquests, written for British boys, which omitted the Tower Bridge would be like an apple dumpling with the apple left out. Londoners are immensely proud of their Tower Bridge, and think almost as much of it as they do of the hoary old Tower from which it takes its name, and beside which it stands. Americans, who flock in thousands to visit the Tower, cast but a glance at the bridge and pass by; but wherever we come from we shall, I think, have an increased admiration for the Tower Bridge by the time we have read the next few pages.

Before we go any farther, just let us see why the Tower Bridge was built. He would think, who did not have to cross them in a hurry, that there were bridges enough in London before it. The trouble is that there are not bridges enough. Father Thames has been a veritable father to London, for he has made it the greatest city and the greatest port in the world, although Londoners are apt to claim that credit for themselves. None the less, Father Thames is a nuisance and an obstruction to people who find themselves on the wrong side of him at the wrong moment, a state of affairs which is so common that it is proposed to throw yet another bridge across him, opposite St. Paul's Cathedral. Of course, the best thing that could be done with Father Thames would be to get rid of him altogether, or to cover him up with a bridge extending from Chelsea to the Pool, and to divert him to a sort of watery back street, where he would be less in the way.

No, there are not bridges enough, nor will there ever be; and the Tower Bridge was built as a slight mitigation of the misfortune of finding oneself on the wrong side of the river at the wrong time. Not content with the thirteen bridges that they already possessed—to say nothing of half a dozen railway bridges—Londoners decided in 1885 that they must have another. It was like their unreasonableness to want it put just where it was most difficult to put it, below London Bridge. There they would have it, and nowhere else. Then the shipowners and wharfingers in the Upper Pool had something to say, and made such a fuss that one might have thought that London belonged to them. "What," they said, "is to become of our ships? You may not be aware of the fact, but we assure you, most solemnly, that ships have masts; and, having masts, they can't get under a bridge unless you build it so high up that your horses will never be able to climb the approaches. Of course, that is your look-out; otherwise, no, thank you—not for us!" What they said looked unanswerable, until one enterprising gentleman came forward with a scheme for a flying bridge—that is, a steam ferry—another suggested a tunnel, and a third—for all I know to the contrary—a cross-river balloon service, and so on. Londoners nursed their grievances and looked very glum, until



Phot: M. Wright, Middlesbrough

THE MIDDLESBROUGH TRANSPORTER BRIDGE

Total length, 850 feet; length of span between towers, 570 feet; height from high-water level to under side of girders over the river, 177 feet; height from water level to top of towers, 225 feet; capacity of travelling car, 500 to 600 passengers and 6 vehicles

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an architect named Sir Horace Jones, and an engineer named Mr. J. Wolfe Barry—later on he was persuaded to drop the "Mr."—came forward with a design for a bridge which was high enough for the masts of the shipowners and wharfingers, and low enough for the overworked horses in drays belonging to brewers and others. "Just the very thing!" said everybody. Of course it was. Everybody was satisfied, and so he ought to be. Thus the Tower Bridge came into existence. It cost London a great deal of money—£800,000—but it has been well worth it, for it relieved the city of her dread disease, congestion of her street traffic, for many years.

The Tower Bridge is a combination of three types. The most imposing portion, the middle, is a bascule bridge, the modern representative of the drawbridges that our forefathers placed across their moats, to give access to the front doors of their castles for themselves, and to keep out objectionable visitors. The side spans are suspension bridges, and the high-level bridge up at the top is a continuous girder bridge, built on the cantilever principle.

The piers on which the great towers are built are very fine fellows indeed, and between them can bear a strain of 70,000 tons without slipping or sinking, or doing anything foolish of that kind. Their foundations are not far short of 100 feet below the water level. You do not need to be told that a pier that requires to be able to carry the deadweight of 300 full-sized express locomotives on its back must have a very firm foundation indeed, and, roughly, that is the equivalent weight which each pier of the Tower Bridge has to carry. They are almost the largest masonry piers in the world, for it so happens that the bed of the Thames is very unstable.

The method which the engineers adopted for making the foundations deep down under the Thames mud is very interesting. They were built with the help of caissons, but these were quite unlike those about which we read in a previous chapter. In the case of the Tower Bridge the caissons were simply large boxes, without tops or bottoms. They were 28 feet square, and were made of steel plates. There were ten of these square caissons and four triangular ones, and eight of the former were let down into the water in two rows of four, a space of 2½ feet being left between the caissons. Another caisson was placed at each end, between the rows, and the triangular ones came in at the corners. They thus formed a sort of disconnected hollow steel wall, within which the piers were eventually to arise.

As each section was lowered into the water divers were sent down into it. They cleared away the soft mud that lay at the bottom of the river, and the sand and gravel underneath the mud, and allowed the caisson to settle down in a perfectly upright position. Section after section was lowered on to the top of the first, the increasing weight sending the whole down more deeply into the ground. When, at a depth of 19 feet of mud and gravel, a fairly hard bottom was reached, each caisson was pumped dry. Navvies were next sent down to dig away the bottom of the river, so that the foundations would go down still farther into the clay.

This work does not sound much to talk about, but, as a matter of fact, it was very important and very difficult. Mind you, each of the fourteen caissons was a separate construction, and had to be separately sunk. If one of them had slipped down at one end, or got out of the vertical in any manner, or given way before the pressure of water outside it, it would have been a terrible business to get it right again. The contractors were much hampered by want of room for piers and staging, for they were obliged to leave a clear way of 160 feet between the piers while they were being built.

Each caisson was "undercut", by which is meant that a cavity was first dug out beneath it and then filled with concrete, so that it rested on a solid bed of that material. A firm foundation was thus found for all the separate caissons, which were then themselves filled with concrete. Then the spaces between them were closed up, the water was pumped out from between the rows, and that space was built up with solid masonry and granite, bricks and concrete.

Before the piers were finished there were built into them great bolts, which were used for attaching the columns of the steelwork in the towers. The towers, it should be explained, are not built of stone, as they appear to be, but are made of steel, clothed with stone in order that they may harmonize with the Tower of London. At the corner of each tower is a great steel column.

When the piers had grown a few feet in height, stagings were erected on them; and upon these were placed cranes for hoisting up the steel plates into position for the riveters to fasten. Up and up they went, columns and staging together. When they were 60 feet above the ground level the columns were joined together by means of plate girders, 6 feet deep. These form the first landing in the towers, and when they had been put in place they were used as a stage to support the scaffolding for building the columns still higher. Twenty-eight feet higher up the columns were again tied by four horizontal girders; and still other 28 feet higher—that is, 116 feet above the piers—were fixed the great girders to which are "anchored", or fixed, the cantilevers for the high-level footway. As the columns were built up they were braced diagonally, smaller girders being fastened from corner to corner after the manner of lattice work, thus better enabling the towers to resist the pressure of the wind.

The high-level bridge was built out cantilever fashion from each tower simultaneously, the "false-work" connecting the middle girders being finally cut, as was done in the case of the Forth Bridge. This top bridge was built partly to allow foot passengers to cross the river at times when the bascules are raised; but it has also another function, and a far more important one, for its girders carry the great suspension chains that hold up the 160-feet side spans of the bridge. The small towers at each end of the bridge are the abutment towers, and support the chains from which the side spans are suspended.

These suspension chains are very wonderful, and unlike any other chain you have ever seen. In the first place, think of a chain that has only two "links", each of which is built up of steel plates riveted together, and is joined at its ends by means of great bolts, and you will have a good idea of what the suspension chains of the Tower Bridge are like. Look at the bridge, and you will see that the chains rise from the shore on each side of the river to the top of the abutment towers; this part is not strictly a link, but is called a tie. The chains come out of the river side of the abutment towers, dip down to the middle of the side bridges, and then rise again to the top of the main towers. Here are the two "links" of the chains. At the top of each tower the chains are connected to the great tie that runs along the high-level bridge, and to the other end of this tie is joined the longer link of the chain on the other side of the river; so you see that the chains are longer than the bridge itself—more than a mile long, in fact.

Let us see now how they were made. First of all, on the shore at both ends of the bridge great concrete "anchorages" were built, below the level of the ground, and in this concrete were fixed mighty girders. To the girders were fastened, by means of "pins" 2 feet in diameter, the first of the ties—those, you remember, that go up to the abutment towers. On the top of the steelwork in these towers are great slabs of steel, on which rest heavy roller bearings. The horizontal ties pass over these rollers, and are connected to the ends of the shoreward ties. At the other ends of the horizontal ties comes the shorter link of the mammoth chain. The chain proper is composed of two main portions or booms, one above the other, and connected with diagonal rods for the purpose of making the chain stronger. The short links and the long links are joined together at the middle of the side bridges, where they are "hooked on", as it were, to the bridge itself. At the top of the main towers, where the long links are joined to the great ties on the high-level bridge, there is another arrangement of steel bearing plates and rollers similar to that on the top of the small abutment towers. Of course, the idea of these roller bearings is to enable the links of the chain to move freely, for they are always in motion. Each of the "eyes"—the holes through which pass the pins that join the ends of the different links and ties together—is at least 2 feet in diameter. These holes had to be widened out to this size—accurately cut out of solid steel an inch thick—while ties and links were actually in position.

The great feature of the Tower Bridge is the middle span of 200 feet, the two great leaves of which it is composed being the largest in the world. Each leaf, or bascule, is composed of four main girders, over 150 feet long. The building of the bascules presented some very pretty problems, for the engineers were much hampered by want of room in which to erect them, since they were not allowed to obstruct the river passage in any way. Each bascule moves on a pivot 100 feet from the river end and 50 feet from the shoreward end, and the first thing that was done was to fix on to the piers the steel plates and roller bearings on which the pivot moves. Then was built the attachment—a complicated mass of girders and trusses—by means of which the great girders of the bascules are fastened to the pivots; and when this had been done the constructors were ready to deal with the first lengths of the girders. These were swung in under a staging built up on the piers, and were fastened up in their proper positions. Meanwhile a temporary pivot was made, and the young girders were keyed on to it; the semicircular racks on which the bascules move were riveted to the girders, and the arrangement of cog wheels through which the lifting power is carried to the girders was temporarily put in. At this stage the girders were turned up, so that the river ends pointed upwards; and the temporary pivots were taken out and the proper ones —neat little steel pins only 48 feet long and 21 inches thick; mere trifles weighing 25 tons each—were put in. Then girder after girder was added in an upward direction, until the bascules were completed to their full length.

Although the bascules weigh over 1000 tons each, they are beautifully balanced, the shorter ends being weighted with 350 tons of ballast to accomplish this. If it were not for the wind pressure against their surfaces, for the friction of the racks and bearings, and for the bascules' own disinclination to move—a tendency which we call inertia—a child would be able to work them quite easily. This sounds rather astonishing; but it should be clear to you when you remember that the hydraulic rams that move them up and down so often every day do not actually have to *lift* the bascules, but to swing them—a very different thing. If you have ever pushed a cart, or a bicycle even, you must know that the greatest effort is required to get the thing into motion at the start, and that once it is started and the inertia overcome it goes much more easily. It is just the same with the see-saw, and the Tower Bridge bascules are simply huge see-saws. Indeed, the French child makes no bones about it, and when he wants to play at see-saw, says, "*Jouons à la bascule*".

A little child could move the Tower Bridge bascules *if* it were not for their inertia; but this is a very big "if", and as a matter of fact very powerful steam engines are necessary to supply the water to the hydraulic rams required to move them, each of which works at a pressure of 750 pounds to the square inch. Hydraulic power is also required for operating the bolts that lock the ends of the bascules when they come together after being open.

The bridge boasts of some elaborate safety appliances to prevent the bascules from moving too far if anything went wrong. There is also an automatic arrangement by which they would be brought safely to rest if anything happened to the engineer while they were in motion, a system of valves cutting off the supply of power, without which they can move neither up nor down.

What! you want *figures*? Well, here they are—quite enough of them to enable you to spend some time in reflecting on the immensity of London's biggest bridge, and the labour of building it. There are (so I have been told) five miles of steel plates in the bridge, representing, with the iron work, a grand total of 19,000 tons. This, one would think, would have built a very pretty little bridge of itself, but in reality it forms only a relatively small portion of the Tower Bridge, for there were used up as well 24 millions of bricks, 72,000 cubic yards of concrete, and 415,000 cubic feet of granite. Compared with the Monument—but no, I don't think we can, again!

CHAPTER V

The Tunnel Builders

In one direction a speck of daylight, as though the sun looked at us through a peephole. In the opposite, a narrowing vista of electric lights. On the ground, a thick mass of greasy mud, through which men in top boots make a squelching progress. Water dripping from the sides, water dripping from the roof; green slime and ugly fungi everywhere; an oppressive air, moisture-laden, and smelling of many vaults. A tram line roughly laid on rough sleepers in the mud; muddy ponies drawing trucks of mud and water, urged by boys who look as though they might be made of mud—turned into mud, perhaps, by some genii of that substance, as a punishment for a too great fondness for mud pies. Mud everywhere. Great balks and planks of timber reared in fantastic shapes, made more fantastic still by muddy smears and blotches. Men around whose very voices seem to have been thickened unnaturally, as though the mud had penetrated to their lungs. A very world of mud: it seems as if all the gutters ever made by man were emptied here, and all the crossing sweepers were condemned to shovel this mud for evermore.

Such is a tunnel in construction, before it has been nicely lined with bricks, before it has been drained, before the clean ballast has been brought to cover the sleepers, all ready for our passage through it in a swift, smooth-running train. Such is a tunnel!—quite a common or garden tunnel too, as might be made in any muddy district on any line of railway you could name. It does not sound as though it were going to be a very interesting subject for inclusion in our book of conquests. It seems rather depressing, in fact, like a visit to a musty wine cellar, in which the sun that made the wine shall shine on it no more; or like a November day in London. But we must have tunnels, like other dreary places wherein the sun can never shine; and if you come to think of it, it *is* a pretty bold thing for a handful of little men to pit their strength against a mighty hill, to bring their puny tools and cut a hole right through it like a company of human moles.

If somebody came to you and commanded you to make a tunnel through a certain hill, under pain of the most frightful penalties you can imagine if you failed, you would, I suspect, feel remarkably uncomfortable. You might be able to do the boring all right, if the hill were considerate enough to be composed of soft material; and you might even contrive to support the tunnel roof so that it would not fall down on you. But when it came to making up your mind that if you bored into the hill at a certain point you would be quite sure of coming out at a certain point—at one definite spot on a map out of the hundreds of spots at which you *might* come out—the task would seem—of course assuming that we are ignorant of the matter—a hazardous one, would it not?

When the engineer says to us: "Now, look here, I am going to make a tunnel through this mountain; one entrance will be at this point here, and the other at that point there, five miles away," there is something almost uncanny about his ways, and we wonder whether he is not a new sort of magician. As a matter of fact, he is a very old magician, and people found out that he was a hollow sham—as hollow as his tunnel — many centuries ago. His conjuring tricks are almost as old as the hills, and he carries the secrets of them in a little book in his waistcoat pocket. The secrets of his little book—and these, mark you, are the secret of his wonders—were told before people wore waistcoats. They were discovered by very useful but rather prosy old gentlemen, who were called mathematicians: our old school friend Euclid was one of them; and there was, among many others, an eminent gentleman who rejoiced in the name of Pythagoras, of whom you have doubtless heard. These useful people—and others more modern—put their brains together, to make burrowing under the ground as easy and as certain as erecting fences over it. The magic of this art is carried in the breast (or the waistcoat pocket) of our modern friend the surveyor. He likes to make believe that he is really a magician—a sort of superior conjurer, in fact—but nowadays people know better, and accept him at his true value, which is none the less a very high value indeed.

Tunnel making is a very ancient art—almost as ancient as the gentleman with the long name that I mentioned just now. Babylon had a wonderful tunnel connecting two parts of the city on opposite banks of the river. The Romans cut tunnels in order to supply their cities with water. However, we are not concerned just now with triumphs of engineering which were accomplished centuries before the coming of Christ, but with those with which we are nowadays familiar. I propose in this chapter and the following one to tell you the stories of some of the great modern tunnels of the world, but before we can proceed to these we must make ourselves acquainted with the rudiments of tunnel engineering.

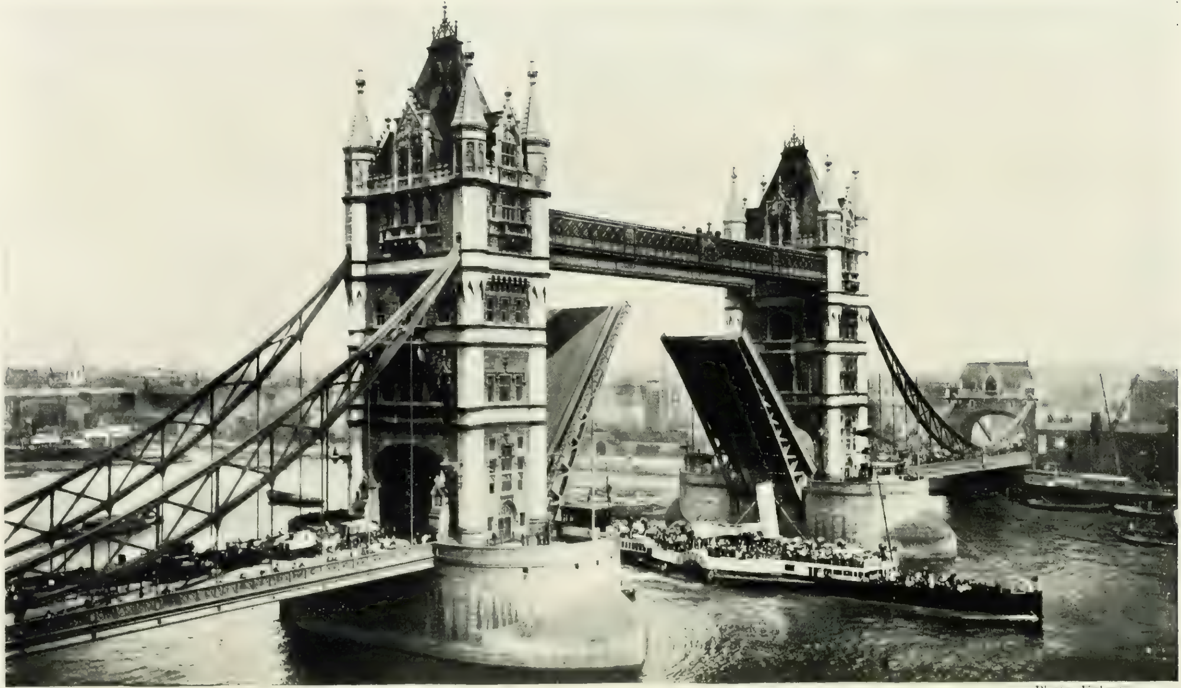
What I am going to tell you may possibly meet with your displeasure, on the grounds that it is technical or uninteresting. Very well, then, you are at perfect liberty to skip the next few pages. But I am afraid that if you do you will not be able to understand thoroughly what follows; and this would be a pity, because we have come to deal with a very fascinating branch of engineering—fascinating, because we are going to explore the secrets that lie buried from our ken in the heart of the hills; fascinating, also, because the work that we shall follow is attended with great danger, and calls forth courage and perseverance in a greater degree than does the execution of any other of the great works of the engineer.

When a tunnel is to be built through a hill or under a river, the first part of the work is undertaken by that useful gentleman the surveyor, who takes his levels and angles, and draws his plans, and decides what is to be the direction of the tunnel—whether it is to be straight or curved, what are to be the gradients, and so forth. Then come the boring parties, whose business it is to discover of what sort of stuff the ground through which the tunnel will have to pass is made. These trial borings, as they are called, are very important, and a great deal of the rapid and successful driving of the tunnel depends on the results obtained by them. The borers will discover whether the tunnel will have to be cut through rock, and, if so, whether this will be easy or difficult to cut through; or whether the interior of the hill is of clay, or gravel, or something else. The boring tools are either chisels or augers. When the chisels are used an up-and-down motion is given to them by machinery, and they are thus made to chip a way for themselves in the ground. The augers have hollow stems, and when they are rotated in the borehole bring up to the surface the debris caused by the chisels. It is by means of this debris that the engineers are enabled to discover of what the strata through which the tunnel will pass are composed. The boring tools are fixed to hollow rods, more rods being added as the hole gets deeper and deeper. The tools have to be changed frequently, and sometimes they break. When this happens special tools are lowered into the borehole, which is only a few inches in diameter, in order to recover them; but if a broken tool is so firmly stuck in the ground that it cannot be moved, the partially made hole has to be abandoned, and a new one made. An interesting anecdote in connection with a broken boring tool is told by Mr. Francis Fox, who says that the story which I am going to repeat was told to him by Mr. W. H. Barlow, a former chief engineer of the Midland Railway.

A borehole some 6 inches or 8 inches in diameter had been sunk to a depth of 600 feet when the tool broke, became detached, and remained fixed at the bottom. Every possible device was adopted for its recovery, but it proved immovable, and the hole was reluctantly abandoned.

"A few days afterwards," says Mr. Fox, "a working man came into Mr. Barlow's office and said: 'I understand you have lost your boring tool, and are abandoning the hole; but, before doing so, I have come to make the following offer, which, if you accept, will save the boring and all the expense which has been incurred!' Mr. Barlow asked what the conditions were, and the man said there were three. First, that a close fence 9 feet in height should be fixed round the hole, to prevent anyone seeing what was done; secondly, that a policeman should be on duty to keep inquisitive persons at least 50 yards away; and thirdly, that if he brought the tool back he should receive £30. As the offer was made on the 'no cure no pay' principle, and the company in the event of failure would only lose the cost of the fence, Mr. Barlow accepted the man's offer. When all was ready the man went inside the fence, accompanied by a boy, and apparently took nothing with him but a long coil of rope. At the end of a few hours he walked into Mr. Barlow's office with the missing tool, and the hole was saved. The money was at once paid, and then he was asked how he had done it. He replied that it was his secret, and he did not intend to divulge it to anyone. Mr. Barlow suggested that he should put the description into writing so that future generations might benefit; but the man simply replied: 'When I die the secret dies with me', and to this day no one has the slightest idea as to how this feat was accomplished."

When the nature of the ground has been tested by the trial borings, and the engineers know what to expect, a start is made with the actual cutting of the tunnel. Sometimes the headings (that is, the faces of the earth at which the men work) are commenced one at each side of the hill to be pierced—for we are supposing the case of a tunnel of moderate length which is to be cut through a hill of moderate height—so that each party cuts its way inward, and will eventually meet the other in the centre of the hill.



Photo, Valentine

THE TOWER BRIDGE, LONDON

A combination of suspension and bascule types, the bascules being the largest in the world. The central span is 200 feet wide.

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But as often as not this process is reversed, and the men start in the centre of the hill—back to back—and burrow outwards. Of course, in the latter case a shaft has to be sunk, like a pit, before the headings can be made, and this is only possible where the hill is not very high: obviously, it would be quite out of the question in a tunnel through a mountain, or under a river.

The engineer's difficulties often begin with the sinking of the shaft, if it has to be driven through a water-bearing material, such as sand or gravel. When the water becomes very troublesome he sometimes resorts to the use of iron or steel rings, which, when bolted together by means of flanges on the insides of them, to form a continuous metal cylinder, and sunk somewhat after the manner of bridge cylinders, effectually keep out the water. Latterly, however, some brilliant chemists have discovered a process by which water can be held back, so natural and yet so wonderful that it must command the admiration of all of us. It is, in short, so astonishing a method that it almost takes our breath away to read of it, although it consists of nothing more or less than sealing up the water-bearing strata *by freezing it.* When the engineer, in sinking a shaft, taps a subterranean river that defies all the efforts of the most powerful pumps he can bring against it, and renders "tubbing" impossible (tubbing is the iron or steel lining mentioned above), he sinks a number of little boreholes round the flooded shaft, and in these he puts freezing tubes. These freezing tubes are connected with an ammonia freezing plant, and after a time effectually close up the sources of the water with thick ice. A very interesting chapter might be written on this process, and on artificial freezing in general, but this is not the place for it; so, if you would know all about it, turn up "Anhydrous ammonia" in your encyclopædia, and you will learn of the very wonderful work of that wonderful magician, the modern chemist.

The tunnel shafts serve a double purpose; they are useful for ventilation, and they provide a means of egress for the material excavated from the tunnel. At the bottom of the shaft is a hole below the level of the tunnel called a "sump", and into this the water that finds its way into most tunnels is drained. Generally the shaft does not communicate immediately with the headings or galleries, but is connected with them by a small passage called an adit.

The shaft, or shafts—for sometimes there are more than one—having been sunk, a start can be made with the excavation of the tunnel. The workmen do not at once commence to dig the tunnel to its ultimate height and width, but small "break-ups" are first made, starting in opposite directions from the bottom of the shaft. Sometimes the break-ups are begun at the top of the tunnel, sometimes at the bottom. With the top-heading method the roof of the small passage that is first cut remains as the roof of the finished tunnel; in the bottom-heading method the floor of the heading is the floor of the finished tunnel. When the heading has progressed a little way, the work has to be carefully supported by timbering. As the advance party in the heading cuts its way forward, it is followed by a party that widens out the narrow heading to the proper dimensions of the tunnel; and behind this again come the bricklayers and masons whose business it is to line the excavation.

All this sounds very simple and straightforward, and, having read it, one may be excused for wondering how it happens that quite short tunnels sometimes take many years to complete. The trouble is that below ground the engineer can never be quite certain what sorts of foes he will have to encounter; and of all his enemies water is nearly always the most dangerous and the most difficult to conquer. A subterranean spring may burst upon a working party almost without warning, sweeping away the timbering and drowning men and horses. But if water gives the engineer more trouble than anything else, there are other substances—sand, clay, and some kinds of rocks—that sometimes put his utmost resources to the test, and sorely try his patience.

For the workman, tunnelling is probably the most trying of all forms of engineering triumphs. The work is unpleasant and dangerous in the extreme. It has generally to be carried on in a hot and moisture-laden atmosphere, which sometimes is apt to become unendurable. There is continual danger from falls of earth and rock, from inrushes of water, from the misfiring of blasting charges, and from the noxious fumes of dynamite; and in the case of one tunnel, at least, all the workmen in charge of a boring machine were killed by breathing clouds of dust. All honour, then, to the brave fellows who are content to face such dangers. The battles which these heroes fight with earth and water and foul air are fought so very quietly that we hear little about them; but who shall say that their victories are less worthy of our unstinted praise than the more bloody ones of history?

A few pages back we spoke of the surveyor. The work of this gentleman (who is, you must understand, not a separate person, but really the engineer himself) is so important in connection with tunnelling that it will be interesting if we turn our attention to his ways for a few minutes. In order to attain the proper alignment of the tunnels—in other words, in order that the boring parties shall meet accurately at predetermined spots—what are known as "umbrella wires" are used. Though I have no right to assume that you have mastered the science of triangulation, it is rather difficult to explain clearly why the umbrella wires can assure unfailing accuracy in the meeting of the boring parties; but, put briefly, the manner in which they are used is this. First of all, the engineer takes the measurements of angles between certain objects on the surface—a church spire, a tree, and a chimney-stack might be used for this purpose; or, if a mountain is being pierced and no suitable points of observation exist, the engineer will have to provide posts or columns, which will answer the same purpose. By the help of these and his instruments, he is able to define on his plans the exact centre line of the tunnel. In order to ensure that this imaginary centre line will be accurately followed by the workers below ground, the observations have to be checked as the work proceeds. Thin wires—the umbrella wires already referred to—are suspended from the roof of the tunnel at intervals of a few feet. Weights are attached to the lower ends of the wires, and these weights are immersed in oil, to prevent the wires from swaying. The wires are provided with a very delicate adjustment, by which it is possible to move them from side to side, and so to bring them into the same vertical plane. If, on sighting them through a theodolite, one wire comes immediately in front of the other, and eclipses it, the tunnel is being driven in the proper direction; but if the wires are not in this position, the tunnel has got out of its proper centre line, and must be corrected.

The umbrella wire is so called from the fact that there is fixed on it a small conical hood, or "umbrella", to prevent water from dripping down it. A drop of water running down a wire considerably increases its apparent diameter, and it is very necessary that the observations should be made with the strictest accuracy. An apparently trifling error (as shown by the instruments) might be found to make a difference of several inches when the headings met. Electrical apparatus is sometimes used to tell the engineers when the wires are quite still, and are hanging freely without touching anything.

In very long tunnels even the umbrella wires have been found to give lines that are too thick to be accepted as accurate enough, although the wires are only $\frac{1}{40}$ of an inch in diameter; and in the Simplon Tunnel wires were displaced by beams or slits of light, which came through very fine lines scratched on the darkened screens of acetylene lamps. So accurately was the alignment maintained in this tunnel that when the headings met, it was found that the error was only one of a few inches, a marvellous result when the length of the tunnel—12½ miles—is borne in mind.

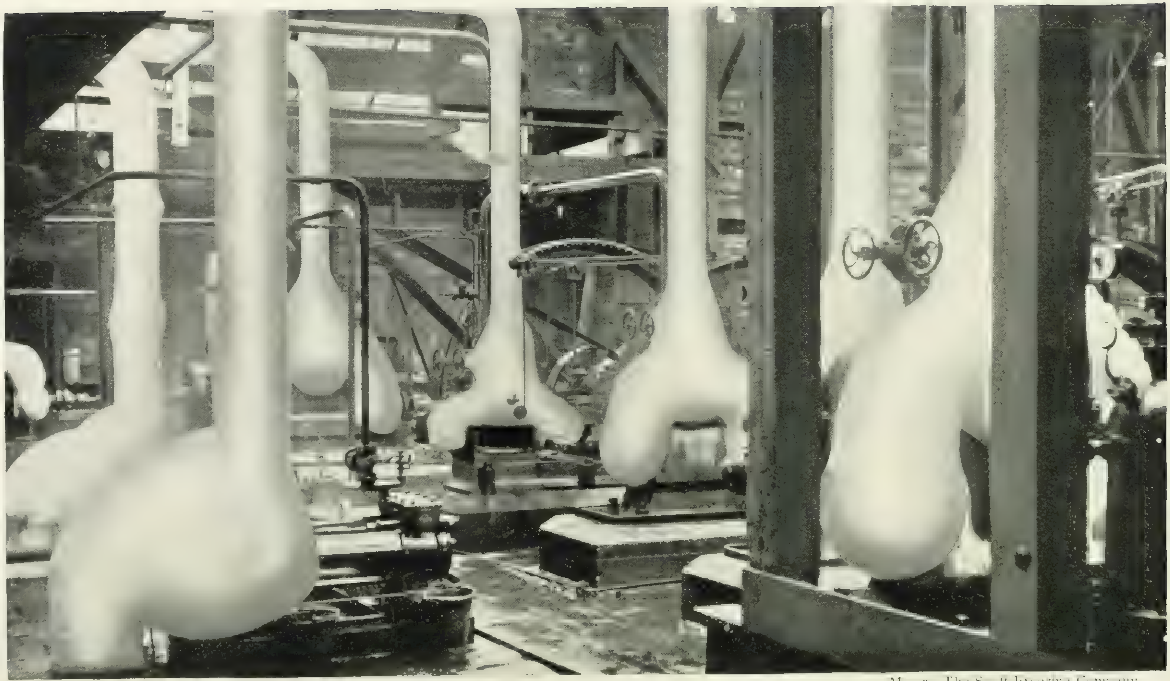
Besides the alignment the level of a tunnel has to be correctly checked, and this is a very important matter. Except when they are carried under water, tunnels are made with a hump in the middle, the gradient falling to either portal in order to assist drainage.

Checking the alignment and taking levels in a tunnel that is half full of water is "no joke". Work is generally stopped periodically, in order that the instruments may be brought into the headings, and the subsequent operations of the engineers are but imperfectly understood by the workmen, who regard them with a certain amount of awe. On one occasion, before observations were to be taken, directions were given to the workmen to remove a certain length of the steel tram rails, from fear that they should affect the compasses. To all appearances this had been done when the surveying party arrived on the scene; but the engineers were soon astounded by the discovery that the instruments were seriously affected by something. The foreman who had been told to move the rails was called, and was asked if he had carried out the instructions given to him. "Oh yes, sir," he said, "I moved them right enough." "Where did you put them?" he was then asked. "Why, sir, under that there muck," he replied, pointing to a heap of excavated material by the side of the heading. Then there was a laugh at the foreman's expense, and it was explained to him that steel did not lose its power of affecting magnetic compasses merely because it happened to be hidden from view.

Some of the most notable tunnels in the world are to be found on the London and Birmingham Railway, once part of the London and North-Western Railway. The tunnels on this line are wonderful, not on account of their length—they are mostly quite short—but because of the difficulties overcome in their construction, and because the men who had to build them showed the qualities of courage and perseverance to a degree that we may well desire to reach. No one can read of these early conquests of the engineer without being amazed at the dauntless pluck and persistence with which he tackled each fresh problem as it arose. The building of the

Kilsby Tunnel, in particular, has been described by a modern writer as the most romantic engineering achievement the world has ever seen. However this may be, the story of Robert Stephenson's patience and certainty of success, as he watched the waters in the flooded tunnel gradually subsiding, is so enthralling that it must come into the list of our triumphs, although it is ancient history; but before we tell the story of the Kilsby Tunnel it will be well to mention two other tunnels on the London and Birmingham Railway, as both are good examples of the dangers and difficulties that early tunnel builders, like those of to-day, had to encounter.

The Primrose Hill Tunnel is close to London, and had to be driven through London clay. Now, clay is one of the most difficult substances to deal with. It cannot be blasted, and the pick and shovel are almost useless against it. At the best of times, with modern methods and machinery, the engineer is never fond of working in clay; and when the contractors started to drive the Primrose Hill Tunnel they found themselves confronted by a material that for a long time baffled all their efforts. They found, indeed, that the stiff, dry London clay was more difficult to work than rock itself. At length they attacked it with axes, and bit by bit the headings were pressed forward. Then it was found that the clay, which has the peculiarity of swelling when exposed to the air, forced the timbering out of position to such an extent as to render the headings unsafe to work in. The engineers then



By kind permission of Messrs. The Shaft-Freezing Company

INTERIOR OF FREEZING-SHED AT A COLLIERY

One method of holding back the water that would otherwise find its way into shafts sunk for mines and tunnels is to freeze it. This view shows the compressors and brine pumps at Easington Colliery.

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adopted the precaution of bricking up the tunnel to within a few feet of the working face as the headings proceeded, and supported the brickwork on very strong timber centering. But even then the clay was by no means conquered, for, ever expanding outwards, and squeezing itself into all the crevices it could find, it forced the mortar from between the bricks, so that the latter began to grind together to such an extent that they would ultimately have ground themselves to powder. A remedy for this was eventually found in the use of harder bricks set in cement, the walls and roof of the tunnel being built to a thickness of 30 inches. The contractor stuck to his task like a hero, and carried it to a successful finish; but the fight with the stubborn clay ruined him in health and resources.

Since the day when the Primrose Hill Tunnel was made engineers have had much experience of tunnelling in clay, as witness the regular rabbit warren of tubes and subways that now exists beneath the streets of London; and in the course of the years they have invented many ingenious devices for cutting through that substance. The men who built the Primrose Hill Tunnel did not know of the hydraulic spade, which cuts into clay as the grocer's scoop cuts into cheese; or of the Greathead shield, or of the cast-iron tunnel lining—and their work loses nothing of its greatness on that account.

Another tunnel on the London and Birmingham Railway that gave the contractors a great deal of trouble, and was responsible for a very terrible accident, was that at Watford. This tunnel was cut through chalk, which might be thought a very harmless sort of material, but which is really very treacherous. If you happen to live in a chalky district you will have noticed, if you are as observant when you take your walks as you ought to be, that the chalk is frequently overlaid by gravel. You can see this in an exposed chalk pit; there are often great holes in the chalk, which are filled with gravel, and this was the cause of the disaster in the building of the Watford Tunnel. In the chalk through which the tunnel passes there were many of these gravel holes, and when the unsuspecting workmen broke into them the gravel rushed down "with such violence as to plough the sides of the tunnel as if bullets had been shot against it". In one of these falls of gravel ten poor fellows were buried. Some of them were mercifully killed outright; others were terribly mutilated.

The tunnel engineer is always being called upon to face unforeseen difficulties, and to brave sudden dangers. Mr. F. S. Williams, who wrote a very interesting history of the Midland Railway, says that he once asked the resident engineer on the Settle and Carlisle branch of the Midland Railway "what was the greatest mess" he was ever in. "'Well,' he replied, after a pause, 'the greatest mess I ever was in was when we were making Birkett Tunnel. The rock was so hard and firm that we thought it would stand without lining; but suddenly the roof in one place came down and made a hole 60 feet high.' 'Sixty feet high,' we said contemplatively. 'How high is that ash tree by the pond?' 'About 30,' he answered; 'the hole in the roof of the tunnel was about twice as big as that tree, and we had to fill it up.' 'Fill it up!' we exclaimed. 'It is easy to fill up a hole that is down in the ground, but how could you fill one that is up in a mountain over your head?' 'We put timbers, sleepers, and what not across from rock to rock, beginning at the highest part of the hole and working downwards, so that no more rock should fall; then we arched the roof round; bedded the top of the arch with debris of all sorts, so that if anything fell it should not injure it. We left nothing overhead but a hole in the crown of the arch big enough for the last workman to crawl through; then we filled up that also.'"

Now let us hear what happened when the Kilsby Tunnel was built. This tunnel passes under a ridge of hills a few miles south-east of Rugby. In the ordinary course of things it would never have become famous as one of the great achievements of Robert Stephenson—perhaps his greatest. It is not much more than a mile long, and when the trial borings were made it was thought that it would pass through a particular kind of shale, which would not present any special difficulties in piercing. The contract was let, and the contractor built a shaft and started operations, all unconscious that the work he was commencing, instead of bringing him fortune and enhancing his reputation, was going to ruin him and kill him. Scarcely, however, had the work of excavation begun when he cut into a large quicksand, overlaid by a bed of clay 40 feet thick. The water in the quicksand burst into the workings, carrying away the roof and very nearly drowning the workmen—the latter being saved, however, by the pluck and presence of mind of one of the engineers, who was in the heading at the time. The men's candles were of course extinguished by the first rush of the water, which continued to pour down on them. Realizing that in a very short while they must be drowned unless they could devise some rapid means of escape, the men set to work to make a raft of the floating timbers. On this they kept above the rising water in the inky blackness of the tunnel, though without the means of propelling their craft. All had given themselves up for lost when it occurred to the engineer, who was a strong swimmer, that he might be able to tow the raft to the bottom of the shaft. Seizing a rope between his teeth, he put the thought into action and struck out in what he believed to be the right direction. Fortune aided his courage, and when completely exhausted he reached the shaft, up which all were taken safely to the surface.

Of course the works in the tunnel were stopped, and pumping engines were set to work; but in spite of the thousands of gallons of water that were raised, the flood continued to pour into the tunnel with unabated fury, and ever rose in the shaft. The contractor was ruined, both in health and purse; and the calamity preyed so strongly on his mind that he became very ill, and died shortly afterwards.

Then the directors of the railway company, who had generously released the unfortunate contractor from his liabilities, had to take the tunnel in hand and decide what was to be done. So they summoned their engineer, Robert Stephenson, and sought his advice. "Are there any means," they asked him, in effect, "by which the tunnel can be saved?" The task seemed hopeless to some of the most eminent engineers of the day, but Robert Stephenson was not the man to allow himself to be defeated easily. "Pump, pump, pump," he said, "and in time the water *must* decrease." Other engineers shook their heads, and even the directors of the company were sceptical of being able to save the works. But the tunnel had already cost a great deal of money, and the time for the completion of the railway was drawing near. To abandon the former to the clutches of the black water surging in its depths would have meant taking the railway out of its destined course, and making a wide detour to avoid the hills. This, after all that had already been done, and the difficulty with which the promoters of the bill for the construction of the railway had obtained the sanction of Parliament, made it imperative that the tunnel should be saved if it were possible. So Stephenson set to work to erect more pumping engines; but as week after week went by, and the waters showed no signs of decreasing, the directors became impatient, and wished that they had listened to the counsels of the other engineers.

Stephenson thought that it would be possible to cut a drift—that is, a passage way—along the heading to the end of the tunnel, with the view of draining off the waters in that way. The excavating party had nearly reached the quicksand, when one day, "while the engineer, his assistants, and the workmen were clustered about the open entrance of the drift-way, they heard a sudden roar, as of distant thunder. It was hoped that the water had burst in —for all the workmen were out of the drift—and that the sand bed would now drain itself off in a natural way. Instead of which, very little water made its appearance, and on examining the inner end of the drift, it was found that the loud noise had been caused by the sudden discharge into it of an immense mass of sand, which had completely choked up the passage, and thus prevented the water from draining off."

The state of affairs was then worse than it had ever been. "You are wasting our time and money," said the discouraged directors; "you must give up this ridiculous attempt to conquer the water, for the water will conquer us." "No," replied Stephenson; "if you give me time I can conquer the water. It is an expensive battle, but to abandon the tunnel will be more expensive still." For he had learnt the lesson of patience in the course of his many engineering adventures, and knew that he *could* conquer the apparently irresistible water. There was no "let-me-try-and-see-if-I-*can*" spirit about him. When he set his brain and his hand to do a thing, his brain and his hand did it.

His next step, after the two reverses just described, was to sink more shafts, with the object of tapping the water in the quicksand at other places; and over each shaft more pumping engines were erected. Pump, pump, pump went the engines, straining day and night at their task, and for eight long weary months—thirty-two weeks, two hundred and twenty-four days—the engineer waited, and waited in vain, for the water to subside. The pumps raised it at the rate of *two thousand gallons a minute for these eight months.* Just let us pause a minute, and enquire what these figures mean. A simple sum in arithmetic often produces an astounding result—astounding, because we do not expect it; and so it is with our present sum. Two thousand gallons a minute for eight months represents a total amount of more than six hundred and forty-five million gallons pumped—enough (so it has been estimated) to fill the river Thames, at high water, between Charing Cross and Woolwich; enough to supply London with water for three days. This, you may say, does not seem very much: but London is a bigger place than we think—so big, indeed, that its oldest and wisest inhabitant does not know how big it is.

Let us take our *Hazell's Annual*, and see how much water London needs. First of all, let us remember that the Metropolitan Water Board supplies an area of 537 square miles, inhabited by over 7,000,000 people—a population nearly equal to that of the two kingdoms of Norway and Sweden, about the same as that of the Dominion of Canada, 2,000,000 more than that of Australia and New Zealand combined, and larger than the whole population of Scotland and Wales by about 1,000,000. We are then less surprised than we should be, if we had not read these figures, when we are told that if a water tank could be built the size of Trafalgar Square (2½ acres), and the height of Nelson's Column, London would empty it twice in every twenty-four hours. In short, London uses in a year a matter of more than 82,000,000,000 gallons of water. Beside these figures the water pumped from the Kilsby Tunnel seems rather insignificant at first, but if you compare them more closely the amount of water pumped out of the tunnel is seen to be more astounding than that of the water supplied to London; for you must not forget that the water that gave the engineers such terrible trouble at Kilsby was contained in a single bed of quicksand, while the water that cleanses and refreshes London—so far as it *can* be cleansed and refreshed—comes from a great river, a hundred reservoirs, and a large number of springs and wells.

The directors of the London and Birmingham

Railway grew more and more dismayed as month after month went by, and at last they told Stephenson that, having taken the advice of other engineers, they had come to the conclusion that the only thing to be done was to abandon the works; and they blamed him for leading them on such a wild-goose chase. We can imagine the feelings of poor Stephenson as he begged the directors to let him continue his operations for a few weeks longer, although not an inch of progress had been made, and as the water came out of the tunnel the money went in. The directors were in despair, but they were also impressed by the dogged perseverance of their engineer. "This man," they thought, "is either a lunatic or a genius;" and, deciding that he was no lunatic, they granted his request, and he was allowed to continue pumping for a fortnight longer. As the eight months had passed without any good appearing, so one week of the fortnight went by. The task seemed hopeless. Hour by hour the level of the water was tested, and the result of the pumping was always—*nothing*. Stephenson doubtless thought much—who could help it?—of his disgrace, if the fortnight passed and the third week ushered in his failure. What shame and laughter and derision would not be hurled at him by those other engineers? What would not be the reproach of the directors who had trusted him? But he kept a brave face before his workmen. And he did *not* fail in his promise, for the second week of the fortnight saw the head of the water lowered. Pump,

pump, pump went the engines, straining all their hundreds of horse-power to beat the mother that worked them. The battle was theirs. In a few days it was possible for the workmen to descend the shaft, and the world rang with the triumph of Robert Stephenson. His troubles and triumphs did not end there, however, for the water still flowed into the headings of the tunnel, washing the mortar away from between the bricks as soon as they were put up. At one time it seemed almost as impossible that the tunnel could ever be lined as it had seemed, a few months before, that it could ever be excavated. But by degrees the work was done, and it stands firm to this day, a monument of engineering pluck and skill.

In all, the number of bricks required to line that tunnel a mile and a third long was thirty-six millions —enough, so a mathematically-inclined writer has told us, to make a footpath a yard wide from London to Aberdeen; or, to be on the safe side, say 500 miles long. The cost of the tunnel, as estimated by the unfortunate contractor who first took it in hand, was £99,000; the actual cost was more than three times that amount, £300,000, or nearly £130 a lineal yard.

CHAPTER VI

The Story of the Severn Tunnel

If you go to the booking office at Paddington Station and ask for a ticket to Cardiff, or Swansea, or any other place in South Wales, the clerk will give you one bearing the words, "via Badminton and Severn Tunnel". That is simply an indication of the route by which you will travel: it means that the train will take you by the "new" route—which is more than thirty years old now—instead of by way of Gloucester; and that you will pass under the estuary of the great river Severn, instead of over it in a steam ferry, as your fathers went. If you will look at your map of England and Wales you will see what a great saving of distance was effected when the Severn Tunnel was built, and it was no longer necessary to go to Gloucester and then down the west bank of the river. That was the way the trains used to go to South Wales; and it was so inconvenient that as traffic grew it was decided to shorten the route by introducing a steam ferry between Avonmouth, on the Gloucestershire side, and Portskewett, on the Monmouthshire side. However, the ferry was not a success, and the Great Western Railway Company then started to provide a continuous and direct line of railway between England and South Wales, the great natural barrier of the Severn being overcome by taking the line under it.

Few of the thousands of people who daily pass through the Severn Tunnel have any idea of its story. As the train whirls them out of the daylight into the dusk of a deep cutting, and a few seconds later into the darkness of the tunnel, some travellers, perhaps, are dimly conscious that it must have been a difficult business to make the tunnel under the river; others will look up at their fellow-passengers, to say "Severn Tunnel", with a knowing smile, before laying aside their papers and composing themselves for "forty winks". Most of them look at their watches, without quite knowing why they do so, forgetting the time before they have finished putting them back in their pockets. Then there is generally the timid old gentleman who, having been in the dark for five minutes, exclaims, "Dear me, this is a very long tunnel!" and begins to get quite fidgety when other ten minutes pass without daylight appearing. And also, of course, there is the cheery individual, with a strikingly yellow suit case, who knows all about it, and insists on enlightening everyone else, only omitting such minor details as the length of the tunnel, when it was built, how long it was building, and so forth.

The Severn Tunnel is the longest one in the British Isles, and is in the front rank of the big tunnels of the world. It is also in the front rank of the big engineering feats of the world; and is right at the very top of the list of subaqueous tunnels. On this account, therefore, a place would have to be found for it among our conquests, even supposing that the story of its making would not provide interesting reading, which it does, as I hope to show in the next few pages. "Ancient history!" say you, my immaculate critic? To be sure! So is the battle of Waterloo; but we hear something of that, from time to time, still.

The tunnel is 4½ miles long, 2½ miles of this being under the Severn. The crown of the tunnel is 50 feet below the bed of the river, and 145 feet below high-water level. You may remember that in the last chapter I told you that tunnels are generally made with a gradient falling towards each end. Of course, this is impossible in the case of a tunnel under a river, for it has to fall on one side and rise on the other. This is the reason why the Severn Tunnel is nearly twice as long as the river is wide; it had to go deep down below the river bed, and in order that the fall under the river should be gradual, the entrances to the tunnel had to be made a considerable way inland. On the Welsh side of the Severn the water is some 40 or 50 feet deeper than it is on the Gloucestershire side; and thus it happens that the tunnel does not attain its greatest depth directly under the middle of the river, but a great deal nearer to the western bank than to the eastern. Perhaps this will become clearer when I explain that the Gloucestershire entrance is only 700 yards from the river's edge, while the Monmouthshire entrance is 1¾ miles away from the water.

The tunnel was commenced towards the end of the year 1872. In 1873 a shaft 200 feet deep had been sunk on the Monmouthshire side, not far from the water's edge. The bottom of this shaft was considerably lower than the level of the tunnel, which is on a rising gradient. As a matter of fact, the tunnel would bisect this shaft about 50 feet from the bottom. You must remember this, or you will not be able to understand thoroughly what follows. Having sunk this shaft (which came to be called the "old" shaft, to distinguish it from others) the engineers commenced to excavate headings from it. Fifty feet from the bottom of the shaft two headings were started in opposite directions, these ultimately forming parts of the tunnel proper. A third heading was also driven riverwards from the *bottom* of the shaft. This heading, which was, of course, 50 feet beneath the line of the tunnel, had a double purpose. It was intended to cut a passage from the bottom of the shaft to the lowest part of the tunnel, a distance of a little less than a mile. This passage or adit was cut partly with the object of ascertaining the nature of the strata through which the tunnel would have to pass, partly as a drain to draw off water which might, and did, find its way into the tunnel workings; and in a third sense it was useful for pushing on the work, as "break-ups" could be started from it in an upward direction, and it could be used as a way whereby materials could be brought in, and the excavated "dirt" taken out. When the headings were far advanced the latter was a matter of extreme difficulty.

It seemed from the outset as though the fates had set their faces against the undertaking. Here was the great and powerful Great Western Railway, with its vast resources—engineers (advised by Sir John Hawkshaw, one of the greatest consultants of the day), men, machines, and money—trying to bore a hole underneath the Severn, and at almost every turn finding itself "stumped", to use a word that fairly expresses the state of affairs. How and why? The answer would take too long to tell, and would not make very profitable reading, or very interesting reading, if you think this is more important. The fact remains that the engineers seemed to be in perpetual trouble. First, the workmen were unskilled, and troublesome to manage; then there was trouble with the ventilation of the headings—or the want of it; there was also trouble with rock, and worse trouble with water. In short, the company wallowed in a literal slough of despond, and the engineers stood still, scratched their heads, and wondered how on earth they could get themselves out of the mess.

Nothing very triumphant about this, you will say. It was indeed a lamentable state of affairs, and the people and the papers began to laugh at it. The directors of the railway company had made the great mistake of undertaking to construct the tunnel themselves, instead of obtaining the services of a contractor with greater experience. As a matter of fact, the company had asked for tenders, but had rejected them on the ground that they were too high. In 1877 they again invited contractors to tender for the work, and again they did not accept one. By that time—nearly five years after the work had been commenced—things were looking almost hopeless, for only about 130 yards forward of a 7-feet tunnel had been constructed; or, in other words, an average progress had been attained of only about *an inch and a half a day*. At this rate the tunnel would have taken more than three hundred years to complete, and the shareholders, who did not much like the idea of waiting so long for a return on the money they were spending, insisted that the work should be either abandoned or hastened forward. To have abandoned the tunnel then would have made the railway company and its engineers the laughing-stock of the world; and, besides, the tunnel was badly needed. The work was therefore pushed forward with real vigour. More shafts were sunk on both sides of the river, and the headings in the tunnel proper were advanced to such an extent in the following two years that by the end of 1879—seven years from the start—a considerable length of tunnel had been excavated and lined.

Perhaps you have heard of October 18, 1879? If you have not, ask your father, who is likely to remember it, even though he may have forgotten the details of the catastrophe that the newspapers of the following day blazoned forth. The work in the headings leading from the shaft that had been sunk first had been proceeding as usual, when suddenly, and without any warning, a jet of water spurted, with a noise like the hiss of steam, through a hole made by a workman's pick. Before the men had time to realize what had happened the hole in the face had grown bigger, and in a few minutes the water was coming into the workings in a torrent which it was impossible to stem. "Fly! Fly for your lives!" was the cry, and the men fought their way to a place of safety. Flowing downhill along the tunnel the water came to the shaft, and leapt down to the lower workings 50 feet below. Fortunately, the other shafts that had been sunk served as means whereby the men were able to reach daylight; and though there were many terrible experiences in the darkness of the flooded headings, there was no loss of life.

A more disastrous state of affairs than that with which the engineers found themselves confronted could hardly be imagined. It is said that on that night men were weeping like little children. And no wonder! For seven long, weary years they had been fighting an unequal battle, and had just begun to congratulate themselves that they had at last got the better of their many foes: yet, in a few hours, here was the tunnel flooded out, and the labour of the seven years undone.

For four months work was at a standstill, while steps were being taken to cut off the Great Spring, as the inrush was called. When the Great Spring burst upon the engineers, the railway company decided that it was high time that the work of making the tunnel was handed over to a contractor. A contract was therefore let to Mr. T. A. Walker; and the subsequent history of the building of the tunnel is the history of that gentleman's courage and perseverance. Mr. Walker undertook to complete the tunnel and its approaches in a certain time and for a certain sum of money. In doing so, he took upon his shoulders the responsibility of carrying out a work of enormous magnitude and difficulty, such as had never before been attempted in the history of modern engineering.

The first thing that Mr. Walker decided to do was to reduce the head of water in the tunnel, so that it should be possible to cut off the Great Spring. With this object powerful pumping engines were erected, and a pumping shaft was sunk; but it was not sufficient merely to go on pumping, month after month, as Stephenson had done at Kilsby. In the Kilsby Tunnel the water came from a bed of quicksand, and could be, and was, drained out altogether; but the Great Spring had its source in a river that flowed down from the neighbouring hills, and would have taken, not months, but years to become exhausted. The only thing that could be done, therefore, was to keep the water under by attacking it with pumps capable of lifting it out of the tunnel more rapidly than it went in, and then to dam up or otherwise close the heading through which the Great Spring had found its way in.

From the very beginning Mr. Walker's operations seemed to be dogged by ill luck. The pumps were found to be unsatisfactory when they arrived, and gave so much trouble that four months elapsed before the water in the shaft had been lowered sufficiently to allow divers to be sent down to dam the source of the Great Spring. When this had at last been done, it was found that the pumps were still unable to do more than prevent the water from gaining ground, and the situation was very little better than it had been before the Great Spring was sealed up; there was no question that it *had* been sealed up, however, for two steel shields had been built in place in the headings leading in both directions from the point where the spring had broken through, thus securely bottling it up. It was then discovered that the water was coming into the lower adit—that which, you will remember, led from the bottom of the original shaft, 200 feet down, and was underneath the tunnel headings, and there was nothing that the engineers could do but go on pumping, pumping, pumping, though their efforts had little effect on the water. Six months after the Great Spring had been dammed—ten months after it had burst into the heading—another accident happened that sorely tried the patience and courage of all engaged in the work. This was the bursting of one of the great pumps. In a few hours the workings were once again full of water as a result of the accident, and the whole weary business had to be started all over again. There was nothing for it but to wait as patiently as possible while the pump was mended, an operation that absorbed another two months; so that it was a year—all but a few days—after the water came into the tunnel before the engineers were in a position to get the better of it.

When the burst pump had been restored to working order, the waters were attacked with a vengeance that we can imagine. Even then little progress was made, and the water still went into the tunnel as fast as it was pumped out. At length it was decided that a sluice in the lower adit must be closed if the tunnel was ever to be pumped dry, and a diver named Lambert undertook to attempt this task. His exploit is one of the bravest in the annals of engineering, and forms a very bright spot in the otherwise depressing picture of the Severn Tunnel.

Lambert undertook to close a sluice door that was situated 1000 feet from the bottom of the shaft. To reach it he had to force his way through the darkness of the water in the narrow tunnel, hampered in his progress by his air-tube and life-line. He went on his perilous journey armed only with a crowbar, and we can but imperfectly imagine what must have been the sensations of this intrepid man as he set out on his lonely and dangerous journey through the tunnel. He could not even say "good-bye" to his fellow-divers, two of whom went with him a little distance, in order that they might bear some of the weight of the 1000 feet of air-tube that he had to drag with him. On he went, and on into the very heart of the black water; now finding his way barred by fallen timbers, now by a drowned pony, now by a heap of rock, but ever pressing on to his all-important goal. He had reached to within 100 feet of the sluice—had performed nine-tenths of his journey, in fact, when the weight of his air-tube became unbearable, and he could carry it no farther. He had failed in his endeavour. Wearily he dragged himself back to the shaft, humiliated, disappointed; but when he stood once more in the bright light of day, the faces around poor Lambert looked almost as glad as they would have done had he succeeded in his mission. His friends—he had many more than he thought—were heartily glad to see him back, although he *had* failed; for everyone had had a creepy feeling in the back while he was under water, as the minutes ran into hours, and the men at the pumps worked at their handles, and there was no signal. It was horrible to think of the brave fellow alone with the darkness and the dead horses and the debris—a solitary creature in a strange element, fighting his way in the narrow tunnel 200 feet beneath them: and worried directors, with pockets more easily touched than their persons, and grim, sad-faced engineers, grown old in the fight with the water, wondered if it were wise to let the diver go; while rough, toilworn navvies, accustomed to facing peril all their lives, didn't wonder, but wished he hadn't gone.

Among the thousands of people in all parts of the country who had read of Lambert's exploit with intense interest was a certain Dr. Fleuss. This gentleman was the inventor of a helmet that was intended to be of service to firemen, miners, sewermen, and others whose business led them into foul air, the wearer of the Fleuss helmet carrying his supply of oxygen on his back, and having no need to rely for his air supply on the efforts of men pumping. Dr. Fleuss asked Lambert whether he would make another attempt to reach the sluice, this time wearing the new helmet, in which its inventor had the greatest confidence. A man less plucky than Lambert would not have ventured on a second journey through that terrible adit; but Lambert had made up his mind that if it were possible for anyone to reach the sluice and close it, he would be the man to do it, and he unhesitatingly agreed to make another journey, and, indeed, as many more as need be. It must have required a considerable moral effort on his part to trust his life to the newfangled and almost untried helmet of Dr. Fleuss. With the ordinary diving suit he had, in his life-line and air-tube, some communication—fragile, to be sure—with the outer world; with the Fleuss helmet he had none. He would be absolutely alone in the dark solitude of the flooded tunnel, with no hope of escape if anything happened to him, and no means of letting the engineers know if he found himself in a deadly plight. On the other hand, the helmet had great advantages which specially fitted it for his task. It was light to carry, and was not encumbered with the tubes that had been the cause of his failure before.

So Lambert wore the helmet, descended the shaft, and disappeared into the black water. In half an hour's time he was back again. He had not been able to reach the sluice, and the second attempt was also a failure. A few days later he started on his third journey. He was away for a much longer time than on the previous attempt, and the watchers at the bank grew more and more anxious as half an hour went by and grew into an hour, and there was no sign of his reappearance. But at last he returned; and when the helmet was removed, and he had recovered from his exhaustion, the engineers listened to an exciting story.

When the diver went down he was fired with a determination to achieve his object. He knew that if he succeeded his act would probably be the means of saving the tunnel; and that if he failed the engineers might have to go on pumping without effect until they had grown old. Therefore the door *must* be reached. The journey was almost too frightful to make more than once in a lifetime, and he was about to make it for the third time; he determined that it should be the last. On and on he blindly groped his way along the heading. A thousand times some dread thought urged him to turn back: now he thought that his oxygen supply had ceased, and he was suffocating; then the water seemed to crush him by its terrible pressure; again, a great heap of debris barred his progress, and he had to wield his crowbar with savage force. On and on, however, he struggled for the full thousand feet. He reached the door—and could not close it. In that sense his journey had been fruitless, and the third attempt had been a failure.

The sluice that Lambert had to screw down was behind a heavy iron door, and when he reached the door he found that he could not move it. For some minutes he struggled with it, feeling every instant that he must turn back if he was to escape with his life, and yet unwilling to leave his task undone just when he seemed so near to its completion. At length he discovered that the door was obstructed by some broken tram lines, and he set to work to tear these up. This done, he fled back to the mouth of the heading, feeling as though all the evil spirits of the black, gripping water were at his heels.

One of those perilous journeys would have been sufficient for most men. Lambert had made three; after each he was disappointed, but not disheartened, and he determined to make a fourth. This time the chances of his success were far brighter. He had got used to wearing the Fleuss helmet—we must not forget that Dr. Fleuss's invention played a very important part in the enterprise—and he had cleared away a great many of the obstructions in the adit. Moreover, he had actually reached the door behind which the sluice was hidden, and there was thus a good ground for hoping that he would be able to reach it again.

On the fourth occasion the engineers and the workmen—all whom the closing of the sluice concerned—found the waiting for the diver's return almost as painful as, after the shock of an explosion, wives and mothers must find the waiting at the pithead for news of the breadwinners below ground. Fears for Lambert's safety, hopes for his success, mingled in their hearts as the minutes ticked out their short lives. "Is he back?" a new-comer would ask, joining a group of grim-faced men, and receiving for answer a shake of the head. "How long has he been down?" "Forty minutes." And the new-comer would form part of the grim-faced group. An hour and a half passed before the news went round that Lambert had returned in safety. Then it became known that he had reached the door and had closed the sluice, whereupon men threw their hats into the air, and cheered and laughed and cried. Lambert had saved the Severn Tunnel, and was hailed as a hero by all who had heard of his brave exploits.

But Mr. Walker and his colleagues were doomed to deeper disappointment than they had yet suffered. Lambert said he had closed the sluice, and there was no reason why his word should have been doubted; the pumps strained harder than ever, but to the intense dismay of the engineers *there was no difference in the level of the water.* For all the good he had done, Lambert might just as well never have made his perilous journeys. There was no doubt that the water was coming into the tunnel as fast as ever it did; and since the sluice had been closed, as Lambert and everyone else thought, it could not be coming in by the way the engineers believed, and so there must be another and unknown inlet. If their fears proved to be justified, there seemed small hope of ever being able to get the better of the water.

Needless to say, the engineers did not stand still. The state of matters demanded that they should get to the bottom of this mystery if it were possible. To pump night and day was the only thing that could be done, so more pumps were sent for and erected. Mr. Walker found that the bills for fuel for the pumping machinery, as well as for the machinery itself, had already put him out of pocket over his contract, although the building of the tunnel was hardly commenced, and seemed, indeed, almost impossible of commencement; however, there was nothing for it but to go on pumping. By sheer force of machinery the water was at length lowered sufficiently to enable an exploring party to venture into the heading. Then it was discovered that, for some extraordinary and unexplained reason, the sluice screwed down the wrong way; that is to say, it had to be turned to the left in order to shut it, instead of to the right, as is usual with all screws, which should always follow the direction of the sun, as the clock does. Poor Lambert, instead of closing the sluice, as he thought, *had really opened it wider.*

Once the sluice had been closed, it became possible to clear the workings of the water. When this had been done the work of excavating and lining the tunnel was pushed ahead with an energy that everyone shared, from Mr. Walker himself to the smallest pony driver. A large number of "break-ups" were made from the headings; the Great Spring was bricked up; and there seemed to be every reason why the tunnel should be brought to a speedy and successful completion. But, as we said at the beginning of this history, the fates seemed to have set their faces against the undertaking. Hitherto the trouble with water had been all in the headings on the Monmouthshire side of the river; now it commenced on the Gloucestershire side. In the spring of 1881 the sea made its way into the workings, with disastrous consequences. It came in through the roof of the heading that had been cut for more than a mile on the Gloucestershire side, and washed away the timbering and the brickwork in completed portions of the tunnel.

For some time the work was again at a standstill while the heading was pumped clear of water, and the spot where the sea had come in was mended. You may wonder how it was possible to mend a weak place in the roof of a tunnel, especially when there were many feet of water overhead. The remedy was really very simple. What the contractor did was to empty a few shiploads of clay into the sea just above the leaky spot—a process so effective that the sea never came into the tunnel in that way again, though it did in another manner, as you shall presently hear.

The task of making the tunnel again went on apace for a while. Before another year had passed, however, Mr. Walker once more found his work beset with many difficulties, this time of a very different character from those that he had faced and conquered before. The workmen began to think that they were being ill-treated, and at last their discontent broke out in open rebellion. Some of them refused to go to work, others smashed tools and machinery, and for a short while there was a strike that paralysed the progress of the tunnel. As a matter of fact, the men's grievances were for the most part imaginary, and the strike was the work of a few discontented miners. For some months past the men had been getting not only mutinous, but what was worse, if that were possible, afraid of working in the headings. Probably the continual flooding, and the ever-present danger of new inrushes of water, disturbed their usual stoical contempt for danger, but whatever the cause may have been, they became subject to sudden qualms of fear; so that, on hearing a strange noise, perhaps, they would suddenly drop their tools and make for the shafts. The most extraordinary outbreak of the kind took place toward the close of 1882. On this occasion two or three hundred men were seized with sudden panic, and rushed towards the shaft, shouting and screaming, fighting and throwing one another down in their frantic efforts to get out of the heading. To add to the confusion the ponies took fright and stampeded through the tunnel, trampling on the bodies of men who had been knocked down. The only cause of the panic was a sudden belief, started by a mischievous workman, that the tunnel was again flooded.

In 1883 the headings that had been driven from both ends met, and there was a clear passage-way—for the most part only 7 feet in diameter—under the river. As if to celebrate this auspicious event in its own peculiar manner, the Great Spring again broke out a couple of weeks later, and in a few hours the workings were completely flooded once more. Eleven years had the engineers been working day and night, and this was the result! Here was the work of those hard-fought years completely undone in as many hours. Would the Severn Tunnel ever be completed? Knowing old gentlemen, and young ones too, shook their heads and doubted. It seemed something like tempting Providence to go on with the work after all that had happened. The tunnel *might*, perhaps, be made, if the contractor and the railway company were not ruined first; but if it *was* made, asked people, who would be so foolish as to trust himself to travel through its haunted depths? The Great Spring had broken out again, but worse was to follow.

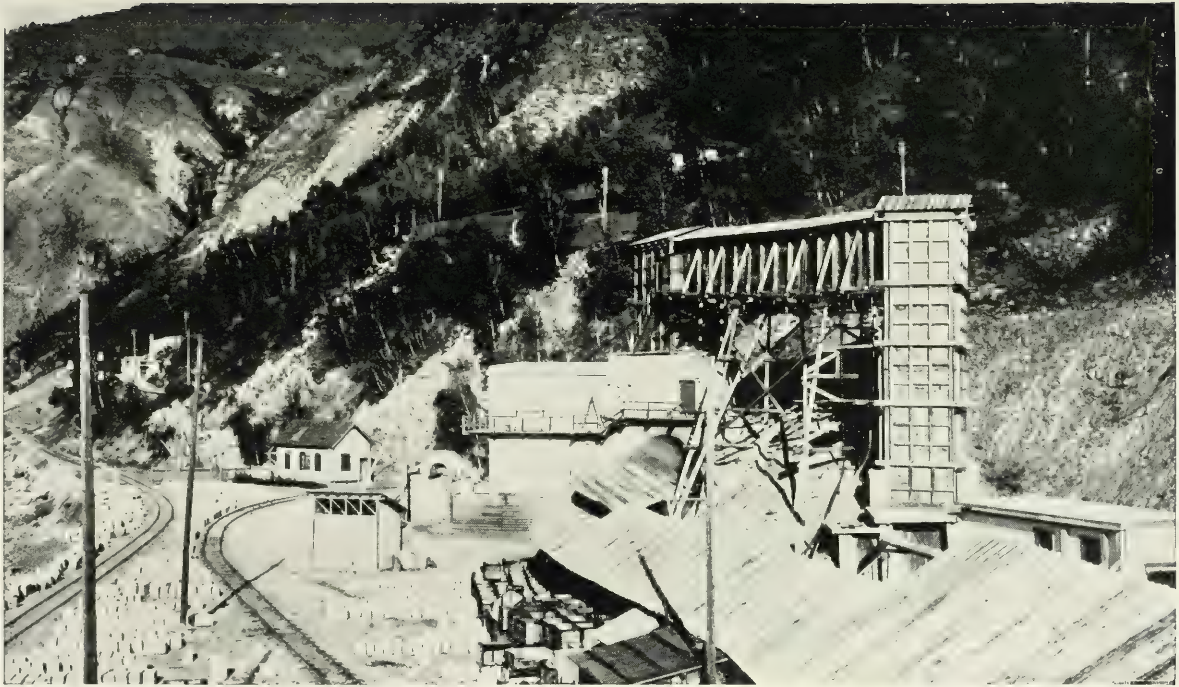
Seven days after the Great Spring water had made its unwelcome reappearance, there happened the greatest of all the catastrophes that marred the making of the tunnel. On the 17th of October, 1883, four years all but a day since the first outbreak of the Great Spring, a great tidal wave swept down the Severn estuary, flooding the country with destructive effect. The Severn is remarkable among the rivers of Great Britain in that it shares with its tributary, the Wye, and the rivers Trent and Solway the phenomenon of a bore. The river is subject to very great rises of tide: at Bristol the rise is sometimes 40 feet; higher up, at Chepstow, where the Wye runs into it, the range of tide is 70 feet. At times of high springtides a great body of water is driven up from the sea into the funnel-shaped estuary of the river, where, spreading out fanwise, it finds its progress barred by the narrowing river, and by the river water flowing down against it in the opposite direction. It therefore becomes piled up, as it were, in a solid wall of water, which is sometimes 6 feet high or more, and rushes up the river with a roar and at a great speed.

An unusually high bore was expected on that memorable night in the history of the Severn Tunnel, but no one dreamed that the waters would rise to a height never before attained, or that they were destined to break through the sea-wall, flooding houses and factories and the ill-fated Severn Tunnel. The tidal wave advanced at a speed of 14 or 15 miles an hour—an immense, irresistible wall of water—burst through the sea-wall, and flowed over low-lying ground until it reached the tunnel shaft, down which it poured in a vast cascade.

Imagine if you can the feelings of the poor men below ground as they first heard and then saw the oncoming flood, and some seconds later were hurled off their feet by its fury. A few struggled to the shaft and climbed to safety, half-dead with terror and fatigue, and blinded by the salt spray. Others were swept from their footholds and hurled to eternity. But the majority of the miners fled before the water, running for their lives up the heading, where it followed them with ever-gaining speed. The lives of these men were saved by the air in the tunnel, which served them as well as—indeed far better than—any other barrier that the wit of man could devise for use in such an emergency. The men and the water were *running uphill*, and this was the circumstance to which the workers owed their lives. As the water flowed up the heading it displaced the air, and forced it against the end, until at last the air was so much compressed that it was able to resist the onward rush of the water—to turn on it, in fact, and hold it back. Then the water, deprived of its momentum, flowed back by gravity to the lower parts of the tunnel. After a long and weary vigil—wet, cold, and hungry—the men were rescued in boats.

And now, of course, the battle with the water had to be commenced all over again, and those good friends of the engineers, the big pumps, were once more called into action. So well did they do their work, so completely did they rout their cunning enemy, that he has never since ventured to attack them in force. Perhaps that is because the pumps have never let him get at them in sufficient force to hurt; for they are always at work, day and night, watching for another effort—it is now a much-belated effort, fortunately—that the water may make on the tunnel, and ready to conquer their natural foe at the first sound of coming battle. They are always at work, these pumps, watchdogs guarding the safety of the traveller in the tunnel, for the Great Spring, although it is bottled up and safely corked, still finds its way into the lower passage, which Lambert knew so well. And they always will be busy, until that day when we shall fly across the broad Severn, and the tunnel will only remind us of a gone and grovelling age.

Thus ends the story of the Severn Tunnel, which was completed without further mishap in 1885. Who shall say that the story of this thirteen years' war is not worthy to rank with the greatest in our history books? Who shall say that its generals and its heroes, its lessons of courage, devotion to duty, and perseverance, are less worthy of our admiration than those that we associate with campaigns fought with more deadly and less useful weapons than the miner's pick and the engineer's theodolite?



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ONE OF THE ENTRANCES TO THE SIMPLON TUNNEL

In order that the miners should not suffer chills by emerging from the great heat of the tunnel workings into the cold air of the Alps, covered alley-ways were constructed, leading from the mouths of the tunnel to heated rest rooms.

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THE BRANDT HYDRAULIC ROCK DRILL IN THE SIMPLON TUNNEL

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CHAPTER VII

Mountain Tunnels and City Tubes

It would be dangerous to say that the railways of a particular country or a particular quarter of the globe surpass, in the magnificence of their engineering works, those of another. India and Peru have wonderful mountain railways, with corkscrew tunnels and slender bridges, flung across wide gorges; Britain has a Severn Tunnel and a Forth Bridge; but only Switzerland, that snug little mountain country, little more than half the size of Scotland, tucked away in the middle of Europe, can claim the distinction of the longest tunnel in the world. In this chapter we shall hear something of the three great tunnels of the Continent.

Let us begin at the beginning—that is, with the tunnel that pierces the "Grand Vallon", or, as it is more generally called, the tunnel of Mont Cenis. The work on it was commenced in 1857, a year that seems to us now to be a very long way off. The building of the Mont Cenis Tunnel was an undertaking of unprecedented magnitude in the history of engineering; it is difficult for us to realize how incredulous the world was half a century ago, or how long and loudly laughed even well-known engineers when the tunnel was first suggested. Nowadays there is no such word as "impossible" in the engineer's vocabulary; but at that time it had not been dropped out, and it was applied to the proposed tunnel in a dozen senses. It was "impossible" for men to carve a way through seven miles and a half of solid rock; it was "impossible" for the tunnel headings to meet without error; it was "impossible" for the workmen to breathe in the workings; it was "impossible" that trains could ever pass through it without all the passengers dying of suffocation. However, like a great many other "impossible" enterprises the Mont Cenis Tunnel was successfully accomplished.

This great tunnel was undertaken by the French, Italian, and Swiss governments, with the object of providing a rapid and easy means of communication between Paris and Turin; and was opened for traffic in 1871, having taken rather more than thirteen years to complete. At first the excavating of the headings was done by hand. Men with picks chipped holes in the hard rock, the holes then being filled with blasting powder, so that the rock was shattered and loosened, and could be easily removed. But the process was slow and tedious; and it became obvious to the engineers that if the work was to be finished in a lifetime better and quicker methods of drilling the rock must be introduced.

You see, when you have a mountain more than 5000 feet high over your head, instead of a sweet

English upland, you cannot bore shafts from which to start headings, and are therefore under the necessity of attacking the mountain on opposite sides and pushing inwards to the centre. In such cases the work of making the tunnel is obviously slower, since fewer "break-ups" can be made. But, as we know, the shafts that can be sunk when the ground above the tunnel is not too deep serve another and more important purpose than that just mentioned. They afford a means of ventilating the tunnel, and of creating in it a natural current of air, which can be but poorly imitated by other methods. The impossibility of sinking shafts adds greatly to the difficulties of Alpine tunnelling. During the building of the Mont Cenis Tunnel many men died as the result of working in impure and dust-laden air, and matters became so serious that compressed air had to be introduced into the workings.

For four years work proceeded very slowly. The rock seemed to become harder as the miners progressed, and had it not been for the invention of the Sommeiller percussive rock drill the tunnel would have taken many years to finish, and the warnings of those who had shouted "impossible" so loud and long might even have proved to have been not without reason. The Sommeiller boring machine has since been surpassed by others of greater power and efficiency; but it was such an ingenious instrument that we are justified in stopping to examine it. Mounted on a truck that ran on the tram rails laid down in the tunnel were eleven long iron cylinders. These cylinders were capable of being moved in any direction, and in each of them were a piston and rod, such as you know belong to a steam engine. Attached to the pistons were eleven sharp, chisel-like instruments, which simultaneously attacked the face of the rock. On compressed air at a pressure of 75 lb. to the square inch being rapidly admitted into the cylinders, first on one side of the pistons and then on the other, the cutting tools "jumped" forward at the face of the rock with such good effect that a hole 1¼ inches in diameter and 3 feet deep could be made in twenty minutes. When eighty of these holes had been made the machine was moved away to a place of safety. Then came men who filled some of the holes with blasting cartridges. When the fuses had been fired, the men retired into a chamber sealed by heavy iron doors until after the explosion; and when that was past, compressed air was forced into the heading to clear away the fumes, and the workmen returned to remove the debris. Owing to the imperfect ventilation of the headings, however, many men were killed by inhaling the fine, dust-like particles of rock raised by the explosions.

On the 1st of March, 1880, an interesting ceremony took place in the heart of the Swiss Alps. On that day nearly four thousand medals were distributed to the workmen who for eight years had been piercing a hole 9½ miles long through the heart of the great St. Gothard. The St. Gothard Tunnel, connecting the railways of Switzerland and Italy, was commenced in 1872, a year after the Mont Cenis Tunnel had been opened, and was ready for traffic ten years later. Although the St. Gothard is 1½ miles longer than that through the "Grand Vallon", its building occupied three years less time. This circumstance helps us to realize what great strides had been made in the science of tunnelling in a few short years. Greater experience, better-skilled workmen, improved rock-boring machinery, better devices for ventilation, and a great many other things lent their aid to the engineers who pierced the St. Gothard.

If you ever have the good fortune to make a journey to Italy via Bâle and Milan, the train will carry you over the St. Gothard railway, of the total length of which the great tunnel occupies nearly one-half. On this short railway may be seen some of the noblest works of man, blending with scenery carved by Nature in her sublimest mood. The cutting of the St. Gothard railway and its wonderful tunnel pales into insignificance when we think of the moulding of the High Alps in the cradle of the earth's crust. What vast engineering was there when, ages and ages ago—ten or more million years, perhaps—what we now call Switzerland was the centre of a land of immense volcanoes! If you would know how the great mountain chains of Central Europe were reared, go to the nearest library and ask for Geikie's *Earth Sculpture*. You are an unnatural boy if you are not held spellbound by the story of how, through the mysterious æons of the earth's making, Mont Blanc's 15,700 feet were raised out of an ocean by the force of great upheavals beneath it; and of how rain and snow, glacier and avalanche, have ever since been carving its peaks, its lakes, and its valleys.

Travelling from Switzerland, the St. Gothard Tunnel is entered at a small place called Geschenen, or Göschenen. Half an hour later the train once more emerges from the blackness of the tunnel at the village of Airola, in Italy. The tunnel cost three million pounds to build, and the twenty-mile railway of which it forms part cost a total sum of nearly four and three-quarter million pounds. Not the least wonderful part of this wonderful railway is the series of spiral or "corkscrew" tunnels. In some of these tunnels—there are six altogether—the train makes a complete circle, and has to twist over itself, just like a corkscrew, in order to climb the heavy gradients that approach the nine-mile tunnel.

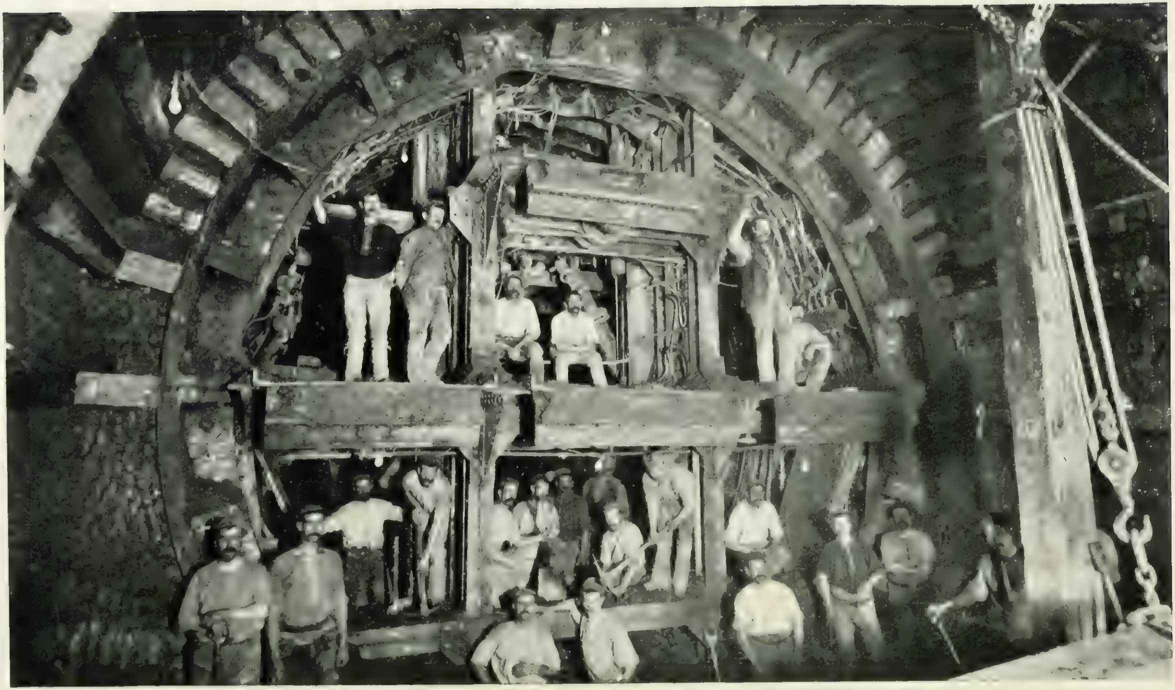
Perhaps the most remarkable thing about the great Alpine tunnels is the unvarying accuracy with which the engineers made their calculations. In the Mont Cenis Tunnel the headings met with an error of less than an inch; in the St. Gothard there was a slightly greater discrepancy, but it was so small as to be less than $\frac{1}{98208}$ of its length. There are several alterations of level in the tunnel, but the calculations were found to be quite correct when the boring parties met. We know that it is only by being *quite sure* of his figures, and leaving nothing to chance, that the engineer is ever able to build these colossal tunnels; and that had the parties at the opposite ends of the St. Gothard differed even a fraction of an inch in the course they proposed to run, their chances of ever meeting at all would have vanished before they had finished the 4¾ miles of boring that each had to accomplish. As a matter of fact, a blunder was made in the driving of one of the St. Gothard headings, for the parties met several days before they were expected to do so, while there was supposed to be a distance of more than 200 feet still separating them.

One of the greatest difficulties in the construction of long tunnels with great masses of earth over them, as in the cases of the Mont Cenis and St. Gothard, which have more than 5000 feet of mountain above them, is the heat of the air in which the men have to work. The farther we go below the earth's crust the hotter it becomes; and although air was always being pumped into the St. Gothard headings, it was found impossible to cool it. The men had to work in an atmosphere of tropical heat, so vitiated and poisonous that the building of the tunnel was marred by a terrible death roll. Indeed, the men who pierce for us a way through the Alpine peaks have to endure terrible hardships. Toiling day after day in the stifling air, often in water, and subjected to increasing danger as the distance from the portals increases, the lot of the miners is far from enviable. Saddest of all was the death in the St.

Gothard Tunnel, before it was quite completed, of M. Favre, the contractor, whose great mind had conceived and carried out the work.

Just as the Mont Cenis Tunnel enjoyed only for a few years the proud distinction of being the longest in the world, so the St. Gothard, which wrested the title from it, was destined to be surpassed in a short time. On June 1, 1906, the Simplon Tunnel was formally opened for traffic, having occupied about six and a half years in building, just half the time taken by the Mont Cenis, and a year and a half less than the time taken to bore through the St. Gothard. The total length of the Simplon Tunnel is 12¼ miles, exceeding that of the St. Gothard and Mont Cenis tunnels by about 3 and 4¼ miles respectively. Boring was commenced at each end in August, 1898, and the headings met in February, 1905.

The Simplon Tunnel differs from its great neighbours not only in its greater length and the shorter time taken to build it, but in other important particulars. For instance, it passes through the mountain at a much lower altitude than either the Mont Cenis or the St. Gothard tunnel, and the approaches are therefore much easier, enabling the trains to be more quickly and economically worked. Another difference is that the up and down lines are not contained in the same tunnel, but run in two separate tunnels cut side by side through the mountain, about 50 feet apart, and connected by passages at frequent inter-



DRIVING THE CENTRAL LONDON RAILWAY

Tube railways are driven with the Greathead shield, which is forced forward by power from hydraulic rams. This picture shows the front of a shield.

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vals throughout their length. By making two narrow tunnels instead of one larger one, it was thought that it would be possible to ensure better ventilation, that the boring could be pushed ahead more quickly, and that materials could be more easily brought into or taken out of the tunnel.

The building of a tunnel 12 miles long through the heart of a great mountain is in itself a great achievement; but one of the Simplon's chief claims to distinction is the rapidity with which it was constructed. For a long period the average progress made by the two advance headings was between 20 and 30 feet a day, and only the engineers and miners who accomplished this feat were really aware of how feverish a business is tunnelling through hard rock at such a speed. The contractors were, as a matter of fact, racing against time, for they were subject to very heavy penalties for every day that the completion of the tunnel was delayed beyond the time fixed in the contract; while the workmen themselves were urged in their work by the offer of special payments, over and above their wages, for all the progress they could make above the normal rate of excavation. Undoubtedly this system of encouragement had a great deal to do with the extraordinary speed with which the work was pushed on, but it would have been utterly useless but for the elaborate steps taken by the contractors to ensure the safety and health of their men.

Experience gained in the driving of the earlier

Alpine tunnels had given the engineers an idea of the temperature that the men would have to work in when they reached the centre of a mountain mass 7000 feet high; but they were not altogether prepared for the intense heat that was actually experienced. In the advance workings on the Swiss side the thermometer registered a temperature of 131° F.—that is, a temperature sufficient to burst the average greenhouse thermometer, which is only graded to 130 degrees; a temperature hotter by 30 degrees or more than a midsummer day in Singapore, which is situated less than a hundred miles from the Equator. It would have been impossible, obviously, for men accustomed, for the most part, to the rigorous climate of Central Europe, to work for eight hours at a stretch in a heat as intense as that of a furnace house; means, therefore, had to be taken to reduce the temperature of the tunnel as much as possible, and all sorts of ingenious devices were introduced for effecting this. Vast quantities of air were pumped into the workings, and jets and sprays of water were injected. Indeed, so well was the health of the workers cared for that the list of fatalities was remarkably low. To a great extent this happy result was due to the means taken to protect the men when their work was finished and they left the tunnel for the day. Instead of coming straight from the fierce heat of the tunnel into the chilly air outside—as they had been allowed to do, with terrible results, when the earlier tunnels were built—they passed into specially heated rooms, connected with the entrance to the tunnel by covered ways. In these rooms they changed out of their wet working clothes, which were taken away to be dried; and they had luxurious warm and douche baths, good meals at very small cost, and the use of spacious recreation and resting rooms.

The task of getting the excavated rock out of the headings was one that presented great difficulty. Owing to the distance from the portals pony traction was out of the question, as being too slow. When the Severn Tunnel was being built the removal of the "dirt" and the introduction of the materials for lining the tunnel were problems successfully solved by the use of an endless rope, running over rollers on the floor, to which the skips could be attached as they were filled. There was thus an endless stream of loaded skips passing out of the tunnel and of empty ones passing in, an arrangement that was a vast improvement upon pony haulage. In the Simplon Tunnel the driving of two parallel headings at the same time made the use of locomotives possible. There was a fixed time-table, the trains leaving and arriving in either direction several times a day. If a miner arrived too late to catch the train that was to take him to the seat of his work five or six miles in the mountain, he had to wait several hours for the next. Probably he took good care not to miss the last train home, for he would not care for a six-mile walk at the end of a day's hard labour in a temperature almost high enough to roast potatoes. Ordinary steam locomotives for hauling the trains were, of course, out of the question, on account of the smoke they would have made; the engineers therefore built some very queer-looking engines, with very long, low boilers, and wheels so small that they would have disgraced even a fair-sized model locomotive. The object of the odd-looking boilers was to do away with the necessity for stoking while the trains were inside the tunnel, enough fuel to generate the steam required being put on the fires before the trains started on their journeys. Besides these unusual locomotives, there were others worked by compressed air. Compressed-air locomotives are sometimes used in mines, and their introduction into the headings of the Simplon Tunnel was not their first application to such work. They had only one cylinder, the piston rod of which was connected with the driving wheels by a gearing of cog wheels, and not directly through connecting rods, as in steam locomotives. The compressed air that worked the engines was stored in a number of small cylinders placed where their boilers would have been, had they been steam engines. The air had been compressed to a pressure of 1000 pounds to the square inch—a pressure that would have sufficed to make the engines useful as rock cutters of a rather violent kind, had their engineers cared to let them rush full tilt into the headings. As it was, however, the air was reduced to a more workable pressure before being allowed to enter the cylinders

There were a great number of ingenious tools and machines called into the digging of the tunnel, and of these the most important were the Brandt rock drills. You may remember I told you that one of the things that helped to make the Mont Cenis and St. Gothard tunnels was a percussive or striking rock borer, worked by compressed air at a pressure of 75 pounds to the square inch. The borers used in the Simplon headings were not percussive, but rotary in principle, just like the carpenter's auger. They were worked, not by compressed air at 75 pounds, but by water at a pressure of *1400 pounds to the inch.* These titanic drills must be seen at work, boring a hole 3 inches in diameter through granite as easily as the blacksmith bores through iron, before their powers can be properly appreciated. They are held against the face of the rock by hydraulic rams with a gentle pressure of some 9 or 10 tons, and are slowly revolved by means of other hydraulic rams, which impart a rotary motion to them through an arrangement of gear wheels. The drills or cutters are 3 inches in diameter, are adjustable to almost any angle, and have hollow stems, down which is discharged the waste water from the hydraulic cylinders. This water is a great help to the miner; it keeps the cutter from getting red-hot with friction, it washes the drillings out of the hole, and it also keeps down the deadly dust that would otherwise float in the air and be inhaled. Needless to say, the drills do not last long, and their three teeth or cutting edges are quickly ground away by the friction with the rock. The cutters have then to be re-ground, and this work kept busy quite a large number of men during the making of the Simplon Tunnel, some hundreds of cutters being sharpened, and blunted again, every day.

The completeness and extent of the lesser works that the contractors for the Simplon Tunnel had to carry out are scarcely less wonderful than the great tunnel itself. Owing to the abundance of water power quite close to the site of the tunnel everything that had to be moved—air and water pumps, tools, and machinery—was moved by electricity, the water being harnessed to turn the electric generators. The river was dammed 2 or 3 miles above the works, and the water was brought down in great pipes, more than 3 feet in diameter, made of steel plates. The pipes had to resist a pressure of 250 pounds to the square inch exerted by the water that they led to the turbines, which generated power to the extent of over 1000 horse-power. The turbines in their turn drove the pumps for the hydraulic machinery and the dynamos for the electric light in the tunnel, compressed the air for the workmen to breathe, and provided power as well for a large number of tools and machines in the workshops.

It must not be supposed that, because it was built so quickly, the Simplon Tunnel was built without the engineers meeting and conquering a great many difficulties. Subterranean springs and streams of water had to be kept in check. Some of the springs poured forth into the workings water of a high temperature, thus showing that they had their sources in the heart of the mountain. Others, again, were cold, and filtered through from the outside. A great spring, which was tapped by the miners in the advance heading 2½ miles from the Italian end, flooded the workings with vast quantities of water, and at one time threatened to delay the progress of the work. Yet the water that came roaring into the heading was not altogether an unwelcome visitor; for, being cold water, it helped to reduce the terrible heat in which the miners were working. More troublesome than the water, however, was a bed of mica schist through which the tunnel had to be cut. Mica schist is a substance composed of shining flakes of mica, and is about as soft as clay shale; the rock surrounding it was gneiss, which is almost as hard as granite. The pressure of the rock forced the mica schist into the heading as soon as an opening had been made into the strata in which it occurred, and this hindered the work of the engineers so much that it was several months before a passage could be cut through it. So great was the pressure that it exerted on the timbering in the heading that the props broke, and had to be supplanted by heavy iron girders and supports.

In all tunnels, but especially in very long ones, such as those that pierce the Alps, ventilation is a matter that has to receive very careful attention.

Most of us know, from experience, how unpleasant is the passage of a train through a long tunnel, unless the carriage windows are quite shut; but the long tunnels of Great Britain are sweet and fresh compared with shorter ones on Continental railways, although there have been great improvements in tunnel ventilation during the past few years. The reason why tunnels on Swiss and Italian railways used to be so much more smoky and choky than tunnels in our own country is to be found in the fact that an inferior kind of fuel is used on locomotives abroad. This fuel produces great quantities of dense, sulphurous, evil-smelling smoke, which hangs about in the mountain tunnels for a long time because there are no shafts by which it can escape. There have been cases when, after going through a long tunnel, passengers have been found insensible; and on one occasion both drivers and firemen were overcome by the fumes. The train was a very heavy one, drawn by two powerful engines, and the wind was blowing into the tunnel at the time. Fortunately, one of the men on the second engine was able to keep his senses long enough to get the train to the end of the tunnel and to stop it, before he fell to the footplate. With the idea of overcoming the difficulty of insufficient ventilation many ingenious devices for forcing air into tunnels have been invented, most of them taking the form of fans of one shape or another, some of which have been almost as large in diameter as the tunnels themselves. But in many cases, especially those in which a cheap and abundant supply of water power is available, electric traction offers the best and cheapest remedy for foul tunnels. The trains that pass through the Simplon Tunnel are hauled by electric locomotives, and the journey is not in the least objectionable.

The mention of electric traction brings us naturally to speak of the wonderful and mysterious network of electrically worked tunnels that exists beneath the streets of London and other great cities. The construction of "tube" railways is carried on so rapidly, and with so little fuss and outward evidences of their making, that we are apt to regard them rather carelessly; but the modern subterranean electric railway, running in an iron tube, marks an extraordinary advance in the science of tunnelling, which has been brought about almost entirely within the last thirty years by the perfection of the Greathead shield. Brunel was the inventor of a shield that he used when he was building the Thames Tunnel in 1826. This shield—and by shield is meant a casing or cylinder that encloses and protects the workmen, and cuts a way forward through the clay—was very unsatisfactory in working, as may be judged from the fact that Brunel himself had several times to swim for his life while the tunnel was being built. Like other inventions of that great engineer, his shield was left to other hands to develop, and to Mr. J. H. Greathead belongs the chief credit of improving and perfecting the form of tunnel shield that is now always used.

The first tube railway built with a shield moving forward through the clay was the City and South London, constructed in 1886; and it is hardly too much to say that since that time the stiff clay on which London lies has hardly been free from the great machines that have burrowed through it in all directions. The principal advantage gained by the use of the Greathead shield is the vastly increased speed with which it is possible to drive a tunnel. You may remember, perhaps, what a lot of trouble the building of the Camden Town Tunnel, on the London and Birmingham Railway, gave the contractors, and how heartily they wished that the material through which they were boring had been anything but clay. Nowadays, thanks to the Greathead shield, tunnelling through London clay is as easy as tunnelling through anything else.

Let us see what this wonderful shield is like. We notice, first of all, that it is a big cylinder, built up of strong steel plates bolted together on the insides through lugs provided for the purpose. Its diameter is slightly greater than the tunnel which it is used to bore. If the tunnel is to be 11 feet 8 inches in diameter, the shield will be a foot more in diameter, for a reason that will presently be made clear; and its length is about 7 feet. Attached to the front of the cylinder, or "skin" as it is called, is a ring of very heavy castings, forming the cutting edge. Immediately behind the cutting edge is a vertical steel wall or diaphragm, having in its centre a door about 6 feet high and 4 feet wide. This diaphragm serves as a protection to the workmen in case of a fall of the working face, and it helps also to stiffen the cylinder. Behind the diaphragm are the ram segments. These are heavy iron castings, bolted to the cylinder and to the ring of castings forming the cutting edge, and their function is to carry the hydraulic rams by which the shield is pushed bodily forward. In the shields that are used to build the London tube railways there are generally six rams, but in larger shields, such as those that are used for the station tunnels, which are 22 feet in diameter, there are more. Behind this ring of castings, again, comes the tail of the shield, inside which the iron rings for lining the tunnel are erected.

Having thus shortly described the Greathead shield, let us believe for a few moments that, instead of reader and writer, you and I are eminent engineers, charged with the construction of a tube railway. Having obtained the authority of Parliament to proceed with our plans, and having settled with those unkind people who oppose our scheme by handing over to them a great deal more money than their claims are really worth, we start our operations by sinking shafts at the places where the stations on our line are to be. We have to do this very quietly, and without fuss or mess, for we are terribly afraid of being condemned as a nuisance, and of having our work held up by some misguided busybody who may succeed in persuading the law that we have set our hearts on doing damage to someone or something; so that, except for a hoarding, a scaffold, a winding engine, and an endless procession of carts laden with iron coming in and clay going out, no one need know what we are about. When a shaft has been sunk we send down it a party of highly skilled miners, who first make a little heading, and then, having securely timbered it, widen it out to the full diameter of the tunnel in which the station will be situated. (Of course, I need not remind my readers—I mean my co-engineers—that the tubes in which the trains run are less than half the size of the station tunnels.) Then we send down the shaft the segments of the cast-iron rings with which it is to be lined. When all the parts have been put together, and two or three rings of the lining are erected, we send down to follow these the Greathead shield, in pieces, if we have not sent it down with the rings. The shield is put together so that its tail overlaps the rings, and the rams at the back bear against them. The rams are connected up with the hydraulic power supply, and when all is ready the valves are opened and the great shield is forced slowly forward. A small box-heading is made in the clay in front of the diaphragm, the door in which is opened, so that the material can come through as it is broken down. Around the cast-iron ring that forms the cutting edge of the shield we have arranged a number of steel- or iron-shod piles, 2 or 3 feet long, with their points pressing against the clay, and as the shield moves along the piles are forced into the clay, which is thus loosened and falls down.

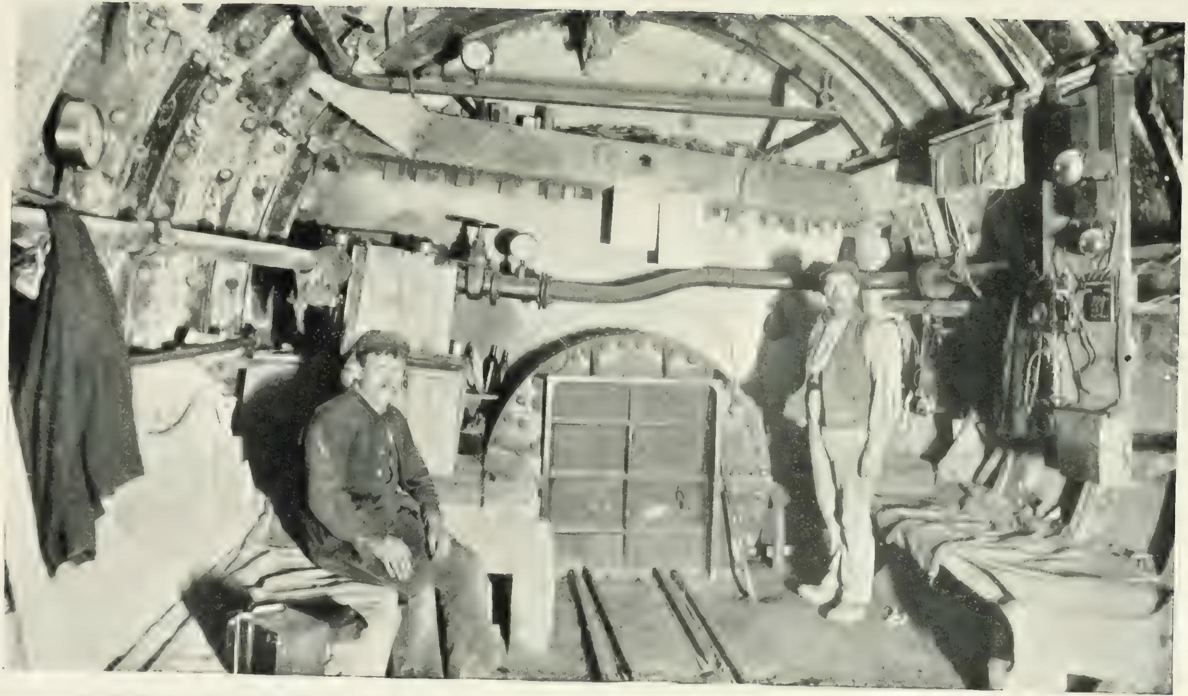
Now let us watch the shield as it forges ahead; let us suppose, in fact, that we are in charge of the valves governing the rams. There are six rams, remember, and the shoe at the end of the piston of each is pressing against the ring of tunnel lining behind it. The word is given, and we are off. What happens? Well, only one thing can happen. When the valves are opened and water is pumped into the cylinders in which the rams work, the rams are forced out, or, rather, the cylinders are forced away from them. Something must move, and as the rings against which the rams are pressing cannot do so, it follows that the cylinders will be forced by the water away from the pistons, and with the cylinders the shield to which they are attached. The rams have a stroke of rather more than the width of a ring or section of tunnel lining, which is generally about 20 inches wide. When the shield has moved forward for the full stroke of the rams, they are withdrawn into the cylinders, leaving a space between the shield and the last ring of tunnel lining, within which a new ring can be erected. The lining rings are made in segments, and cast with flanges, by which they are bolted together on the inside, and are brought up from behind as the shield advances. Sometimes they are put together by hand, and sometimes by mechanical erectors. The mechanical erector consists of a hydraulic ram fixed to the back of the shield, to which are attached chains for lifting the segments into place.

The cast-iron lining rings have to be fitted very accurately, so that they shall bear evenly on all their joints, for they have to withstand great pressure; and so that they shall be quite water-tight. In order to ensure that the joints in the rings shall fit properly, they have to be packed in some way or other, and several substances—tarred rope and sheet lead, for instance—have been used for the purpose. But probably the strongest packing material of all, and one of the most satisfactory, is rust, or, to give it its proper name, rust cement, which is made from iron filings and sal ammoniac.

Since the tunnel lining is erected inside the tail of the shield there is, of course, a space left between the outside of the lining and the surface of the clay; and this space has to be filled up. For this purpose a hole is left in the ring of lining, through which "grout" is injected, the hole being then plugged up. The grouting pan is rather an interesting little apparatus. It consists of a strong steel cylinder, with a paddle wheel revolving inside it, and is provided with a screw-down lid or cover, a tap at the top, and another at the bottom. When it is to be used it is partly filled with water and cement, or lime. Then the lid is screwed down firmly, a man, by turning a handle, works the paddles vigorously, to stir the mixture well, a hose is attached to the lower tap and led to the hole in the lining ring, and another hose connection is made between the upper tap and a compressed-air engine. When the taps are turned on "grout" is blown violently through the hole into the space between the lining and the tunnel, completely filling up the space with a material that soon sets as hard as rock.

The rams that push the Greathead shield through the clay are very powerful indeed. The water is supplied to them at a pressure of about 1 ton to the square inch, so that, reckoning six rams, each 7 inches in diameter, you can soon find out, approximately, what is the total force required to propel the shield. Each ram has a separate valve, and can be worked independently of its brothers, the valves being so placed that one man can easily govern them. When the shield is required to move straight forward all the rams are called into operation at once; but when a curve has to be made only the rams on one side are worked, the shield being thus moved crookedly, if such an expression may be used for an operation that requires the utmost precision. By using the rams independently of one another the man in charge of the shield can steer it up or down, to this side or that, just as he pleases. Of course, the greatest care has to be taken to maintain the correct centre line of the tunnel. To help the engineer to accomplish this, an instrument is placed in a box in front of the diaphragm, and by its means the centre line is continually checked. When we think that several headings, and, consequently, several shields are started at the same time, that each pursues a different course—often a circuitous one—going round corners, uphill and downhill, for a mile or more, and that the shields will meet with such unfailing accuracy that they can be left in to form part of the tunnel lining, then indeed we may feel that the tunnel builder's science is almost beyond the comprehension of ordinary beings like ourselves. Yet it is not so much the tunnel builder who renders these wonders possible as his long-named and long-winded friend, the mathematician of many centuries ago.

After the shield has moved forward, the clay which is broken down by the piles being forced into it has to be removed by hand through the door provided in the diaphragm of the shield. Attempts have been made to do away with the necessity of hand labour by providing machines that can do the excavating, but such machines are not often used for making the 12-foot tunnels of the London tube railways, as there is not very much room in which to work them, and if anything goes wrong with the machinery it is impossible for men to work in the ordinary way until the apparatus has been removed—a matter of considerable delay. When the Central London Railway was built a mechanical excavator of the dredger type was used. This consisted of an endless band, to which was attached a number of buckets. The band was operated by electricity. It could be adjusted to work at any angle, and the buckets scraped at the face of the clay, and scooped it out with



DRIVING THE TUNNEL FOR A TUBE RAILWAY THROUGH WATER-BEARING GROUND

Compressed air has to be employed at the face of the shield, in order to keep out the water, the working chamber being entered through the air lock shown in this photograph.

Fa [illegible]

such good effect that the services of a considerable number of men were dispensed with. Another form of mechanical excavator is like a huge auger, which is fixed in front of the shield and made to revolve as it advances. With this apparatus only nine men are required at work, instead oi fourteen, the usual number without it; and as much as 200 feet of completed tunnel have been made in a week with its help.

When the Greathead shield is driven through water-bearing strata it has to be used in conjunction with a compressed-air apparatus, the object of the air being to hold back the water by equalizing the pressure on both sides of the shield; the shield itself, when it is used with compressed air, does not differ very much from that which has just been described. As soon as the water-bearing ground is met with, a wall or bulkhead is built behind the shield, and behind this bulkhead is placed the airlock. There are doors in the bulkhead and the airlock, and when men and materials are to pass in or out, the bulkhead door is closed before the door in the lock is opened, or vice versa, as the case may be, in the same manner, you will remember, as when we went into and came out of the bridge caisson. The doors at each end of the airlock open inwards; thus, when the working chamber in which the shield is at work is filled with air at a pressure above the ordinary atmosphere, the inner door of the lock—the one communicating with the outer world—is of course kept shut by the difference of pressure, and no one can open it without having first turned on the supply of compressed air, so that the pressure on both sides of the door is equal.

The pressure of air required to hold back the water, and prevent it from flooding the heading, is generally equal to about two atmospheres. When the Blackwall Tunnel under the Thames was built, compressed air was used at a pressure of 36 pounds to the square inch. To provide this great pressure, air compressors of enormous power were required. These engines had a total of 1500 horse-power, and were capable of pumping into the tunnel no less than 600,000 cubic feet of air an hour. As there was a loss of nearly half of the pressure on the journey of the air between the engine-room and the tunnel, owing to the great velocity with which it was forced through the pipes, the engines necessarily had a very much greater capacity than that really required.

Generally, when a shield is being driven through water-bearing material, there are other locks besides the principal one. One of these special locks is situated at a higher level than the main lock, and serves as an emergency exit by which the men can escape, in the event of a fall of the working face, or a sudden inrush of water. The other is a medical lock, into which a man who may be seized with the excruciating pains known as "bends", or compressed-air sickness, can be taken for treatment. You will remember that we touched upon this mysterious disease, which affects workers in compressed air, when we spoke about the caissons used for sinking bridge cylinders. The medical lock is provided with air-valves, and in it the exact atmospheric conditions of the working chamber can be repeated, re-immersion in the high-pressure air being the only thing that affords relief to the sufferer. Fortunately for those who have to work in compressed air, beneath the river or in the heart of the hills, chemists and physicists have recently made great strides in the study of the effects of high-pressure air on the human system, and elaborate precautions are taken to guard against the dreaded sickness.

One of the most wonderful tunnels ever built is that which connects Blackwall, on the north side of the river Thames in London, with Greenwich, on the south side. The tunnel is nearly three-quarters of a mile long, the distance for which it is actually under the river being 1221 feet. It is 27 feet in diameter, and is built of cast-iron rings, a shield having been used just as in the case of a tube railway. The great difficulty in the construction of the tunnel lay in the fact that it had to be driven very close indeed to the river bed; in some places there were only 5 feet of loose gravel above the shield, and, as the water poured through this as through a sieve, the shield may be said, without much exaggeration, to have been driven through the river itself! The reason why the shield had to be kept so close to the river bottom was on account of the great depth of the water—about 70 feet—which necessitated the use of a high air pressure behind the shield in order to balance the head of water.

The shield that was used in making the tunnel was 19 feet 6 inches long and 27 feet 8 inches in diameter, its skin being built up of four thicknesses of steel plates $\frac{5}{8}$ inch thick. As the cylinder had to be driven through several geological formations—water-bearing gravel, hard sand, and different kinds of clay—and as great power was required to propel it, it had to be specially strengthened. The hydraulic rams that worked it had a collective thrust of *5000 tons*; and not only was this tremendous power actually required, but additional rams had to be used at times. The face of the shield was specially protected with a number of shutters having very small openings, the object of which was to help to keep out the water, and to prevent the air from escaping by "blowing" out.

It was, of course, impossible to drive the shield through the loose, water-logged gravel; so the engineers had to make a "blanket" that would protect the shield while passing under this material. This they did by emptying barge-loads of clay into the river, just above the shield, as it progressed. Had this not been done there would have been grave danger of the compressed air behind the shield escaping in such great quantities as to have blown up the bed of the river. As it happened, the clay blanket was, on more than one occasion, a means of saving the tunnel from disaster; for when a "blow" occurred (as not infrequently took place), the ballast was forced into the tunnel by the sudden and violent rush of water. When this happened, the clay above the gravel came down with it, and effectually choked the face, so that no more ballast or water could enter the shield.

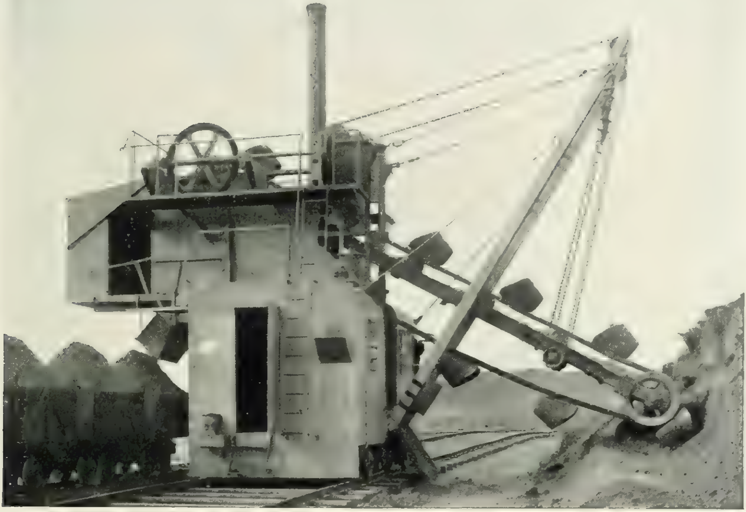
At the best of times the labours of the tunnel builder are far from pleasant; but there is something quite ghastly in the thought of the poor men who had to work, day after day, within a few feet of the bed of the Thames, with the knowledge, acquired by painful experience, that the water might at any minute rush into the heading and sweep them off their feet. After two or three "blows" had occurred, in which the loss of air was so great that the water rushed in and flooded the tunnel to a depth of 8 feet, an upper platform was built in the roof of the tunnel, and this provided a means of escape for the miners in subsequent inrushes of water.

You can imagine that the progress of the shield through the river ballast was very slow. As we have said, the water was in direct communication with the face, and it was found impossible to prevent it from coming into the tunnel by way of the bottom of the shield without special means being taken to keep it out. So those good friends of the tunnel builder, his pumps, had to be called into action. The pumps, however, could not be brought right up to the working face, the "sump" in which they worked being behind the bulkhead separating the finished part of the tunnel from that part which was being driven under the river. The method of forcing the water to within reach of the pumps was interesting. Some large hose pipes, 5 inches in diameter, were brought up to the bottom of the shield, and were connected with the taps admitting the compressed air to the chamber. When the air was turned on it rushed with great force along the pipes, carrying the water with it, and blowing it to the other side of the air-lock bulkhead.

On some days, when the shield was passing through the loose ballast directly under the river, the progress was so slow that a distance of only a foot forward could be accomplished. As the shield, forced onward by the immense power of its hydraulic rams, advanced, the shutters in its face were opened just sufficiently to allow men to dig out the gravel with their hands. These shutters were arranged in tiers, and moved backwards and forwards on slides. The loss of air from the shield was sometimes so great that a man had to be employed at each shutter to keep the space between it and the next one filled up with clay. When the shield had moved an inch or two the top shutters were opened, very gingerly, and the ballast behind was scraped out, sometimes by handfuls and sometimes with the help of small iron rakes. Then the top shutters were closed and screwed down, and a lower row opened, and so forth.

There is hardly a tunnel of any magnitude, in any part of the world, that has not some claim on our admiration; but there is not space here to continue the story of the tunnel builders' exploits and achievements. We must, however, say a word about the latest of the great Alpine tunnels, the Loetschberg, which passes 3500 feet below the summit of the Loetschen Glacier, in Switzerland. This tunnel is remarkable from the fact that its line of direction differs considerably from that originally designed by the engineers. It will always be famous among the world's big tunnels on account of a terrible accident that happened in 1908, when a subterranean river was suddenly tapped, and a large number of workmen were overwhelmed in the mass of sand and gravel brought in by the rush of water. As a result of this disaster work was suspended for a considerable time. Nothing could be done with the water, and it was decided to abandon that part of the workings where the inrush had occurred. The centre-line of the tunnel was therefore diverted for more than a mile, rather more than that length of the flooded tunnel being closed up.

The Loetschberg Tunnel is the third largest in Europe, its length being just over nine miles. It provides the shortest and quickest route between Calais and Boulogne and Milan and Brindisi; and though it cuts off no more than a matter of eighty miles in actual distance, the saving of time on the journey is very considerable. The boring parties attacked the mountain in 1906, and the headings met in 1911, amazingly rapid progress being made in spite of hard rocks, fierce heat, and the disastrous breaking-in of the mountain's secret floods.



A BUCKET EXCAVATOR

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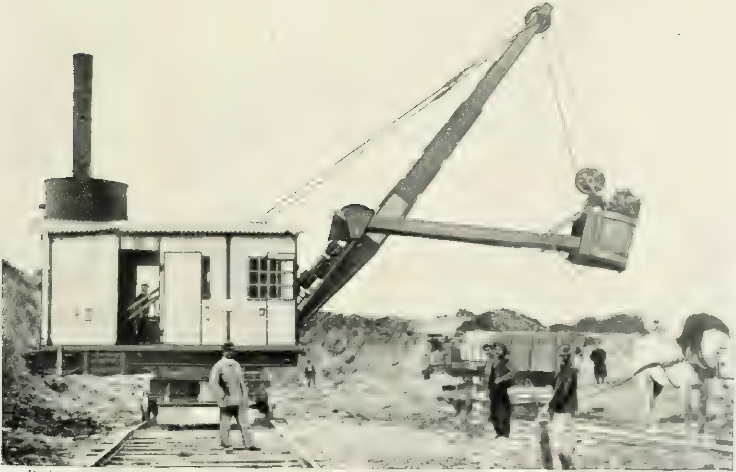

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STEAM NAVVY IN POSITION FOR UNLOADING

These photographs show two types of steam excavators. The dredger-bucket type works continuously, and discharges the "dirt" automatically. The steam navvy shown in the lower picture has to swing round to discharge its load after every cut; but it is stronger and more powerful than the other type, and can deal with harder and rougher ground. *Page 193*

CHAPTER VIII

How Canals are Made

MOST of us, probably, at one time or another have dammed a stream or dug a pond, making ourselves wet and muddy, tired and stiff-limbed. And on these occasions, when we have undertaken to carry out with spade and pick deeply-thought-out schemes for canals and lakes and earthworks in miniature, we have been as happy as the proverbial sandboy, and neither the spoiling of our clothes nor the prospect of paternal wrath has been able to deter us. It is a very good thing for us to be wet and muddy sometimes, although our mothers are not always willing to agree with us. It helps to keep us from becoming snobs, and from being afraid of soiling our hands with the good, wholesome earth; it gives us some idea of the dignity of manual labour, and stiffens our muscles and improves our wind.

Most of us, too, when we have put spade to earth, having nothing better to do, have dug ditches or trenches; and when we dug ditches or trenches we made *canals*. A canal is an artificial channel for water, therefore the gutter by the roadside has as much right to be raised to the dignity of a canal as has the greatest channel ever cut across land for the passage of big ships. The ditches that the farmer digs across his fields to drain them are canals; and such canals as these were in existence hundreds of years before people ever thought of using others as means of communication. The ancient Assyrians and Egyptians had elaborate systems of canals, made for drainage and irrigation, a long time before the coming of Christ. The ancient Chinese, too, were famed for their success as canal builders, and spent large sums of money and employed vast armies of workmen in perfecting their inland waterways. One of these famous Chinese canals is said to have a length of more than 1000 miles. But, great though these works of ancient peoples must have been, they did not exhibit any particular engineering skill; and it was not until the invention of the lock, somewhere in the Middle Ages, that the possibilities of canals as passages for boats containing merchandise came to be considered. Some say that to the Dutch belongs the honour of having first carried canals over uneven land by the introduction of locks; others, again, give the credit to the Italians. However this may be, there is no doubt that canal engineering was a well-developed science on the Continent of Europe before it was seriously taken in hand in Britain. One of the most wonderful of Continental canals was built in France, and connects the Mediterranean with the Atlantic. It was completed in 1680, is 150 miles long, has more than a hundred locks and about fifty aqueducts, and in one part rises to a height of 600 feet above the level of the sea.

Canal building was a long time in coming to England, and when at last it came it was mainly owing to the genius of the two "B's", Brindley and Bridgewater. James Brindley was born at Chapel-en-le-Frith, in Derbyshire, in 1716. From a millwright's apprentice he came to be one of the greatest engineers the world has ever seen, and did for the art of canal building what George Stephenson did for railway building sixty years afterwards. But without the assistance of the Duke of Bridgewater, Brindley's genius might never have found an outlet so well calculated to increase the trade and prosperity of the country, by increasing its means of internal communication. The Duke of Bridgewater has been styled the "father of British inland navigation". He was the proprietor of large collieries at a place called Worsley, which he wished to connect with Manchester; and in order to do this he called to his aid the mechanical skill of Brindley, who designed and built for him a canal that was regarded as one of the wonders of the eighteenth century, and that still commands the admiration of engineers. Brindley decided that his canal should be built on one level; in other words, there were to be no locks. For this it was, of course, necessary to make embankments and cuttings and tunnels; but the crowning feat of all was the great aqueduct that he built to carry the canal over the river Irwell. The Barton

Aqueduct, as it is called, is a massive brick structure, 39 feet above the level of the Irwell, and 200 yards long, over which the Duke's barges were towed as merrily as if they had been on the natural waters of the river, instead of being perched in the air high above it.

From the day that saw the completion of the Duke of Bridgewater's enterprise — an enterprise which the people of his day declared was bound to involve him in ruin, but which, although it greatly impoverished him while it was being carried out, eventually made him a very wealthy man indeed—schemes for canals began to spring up in every corner of the country like mushrooms after a shower of rain. Canals were built here, there, and everywhere; canal promoters pocketed people's money as easily as the promoters of rubber companies did a little while ago; engineers, some good, but most bad, came out of nowhere as if by magic; and the navvies had the time of their generation.

Nowadays, when we speak of a navvy, we think of any rough-handed, coarsely clothed, and villainous-mouthed wielder of the shovel, such as we see opening holes in the roadway, or making a railway cutting, or digging the foundations of a new house. But the word "navvy", like many other words in our language, has a far less general meaning than that which it now conveys. It is a contraction of *navigator*—not the person who sets the course of a ship at sea, but a man who helped to dig the old *navigations*, the big ditches that were made partly for the draining of the fen country and partly for the passage of boats in the swampy districts around the Wash. These navigators were drawn principally from among Lincolnshire labourers, and were men with an extraordinary capacity for hard work and a marvellous aptitude for handling the shovel. When the navigations were finished they travelled over the country in bands, offering their services to the canal engineers. In later years they, or their descendants, built the railway cuttings and embankments, and other earthworks generally; and even went abroad and helped to build the early railways in many Continental countries, in all of which their herculean strength and amazing power of shovelling and wheeling earth were sources of great wonder to the natives, who were totally unable to approach them in skill or endurance.

The study of our canals and their histories is a very interesting one, and one, moreover, that every man —or boy—who has the industrial prosperity of his country at heart should undertake. Millions of pounds have been spent in building our canals, and at one time Britain was in the proud position of being in the very forefront of European countries—excepting only that home of the watery highway, Holland—in regard to the length and utility of her canals. But when the railways came they brought with them interests that conflicted with the canals: sometimes they interfered with them by diverting their traffic to a more advantageous route, for traffic, like water and electricity, will always follow the line of least resistance; but oftener the canals interfered with newly-born railways by retaining, in spite of the intruders, the traffic that they had enjoyed before, in which cases the railways, being the more powerful parties, had to buy up their competitors. In short, the sleepy canal barge and its leisurely horse had to give way to the clattering goods truck and the iron steed. The lock-keepers' cottages became empty, and the lock gates fell to pieces in despair at being so long neglected; green weeds took possession of the pounds, and the waters of the canals themselves were given over to cattle that wallow to be rid of summer flies, to adventurous boys with home-built boats, and to older boys, less actively inclined, who, with casts strong enough to hold a salmon, wait lazily for lazier fish that never seem to bite. For the most part, our canals present a pitiable spectacle, as we look from one derelict to another; but it may be that a brighter era will once more dawn for them, for there are many men, whose opinions we cannot lightly disregard, who would like to clear away the cattle and the mud and the boys, to mend the lock gates and repair the tunnels, and to open our waterways once again, that he who cares may take his merchandise by the ways his grandfathers and great-grandfathers went, more than a century ago.

Of course, it goes without saying that there are many different sorts of canals. First of all, there is what we may call the canal proper, which is entirely an artificial affair, being dug out of the earth and carried through hills and over valleys just like a railway. This sort depends for its supply of water on artificial means, the water being stored in pounds or reservoirs situated at the raised sections of the canal, into which it is allowed to flow as often as need be, to make up for the loss of water through locks, and evaporation, and other outlets. A canal without any water is just as useless as a well in the same state, and the comparative ease or difficulty with which water can be stored is one of the first questions that the canal engineer has to ask himself before he can formulate his schemes. Sometimes the water has to be pumped up from a low to a high level; or, again, it may be emptied backwards and forwards from the locks to the pounds, in order to economize it.

The leakage of water from the high-level portions of canals is a very serious matter; and, as the greater part of it is due to the opening and shutting of the lock gates to enable boats to pass from one level to another, many devices have been introduced with the object of avoiding altogether the necessity for locking, with its usual waste of time and water. Some of these devices are very ingenious, and exist on a larger or smaller scale in most parts of the world. Instead of a passage through locks, what are called perpendicular lifts are sometimes employed for raising the boats from a low to a higher level, or lowering them from a high to a lower, as the case may be. The lift is a large iron tank, which, when the boat has entered and the doors of the tank are closed behind it, is raised up to the higher level by hydraulic power. By this means very large boats can be raised or lowered in a much shorter time than it would take them to pass through several locks one above the other. It does not make any difference to the weight of the tank whether it contains a large boat or a small one, for of course the boat does not add to that weight, but simply displaces by its own weight an equivalent weight of the water in the tank. This is one of the disadvantages of the perpendicular lift, for it takes just as much power to lift or lower a small boat empty as a large one fully loaded. Sometimes, instead of being perpendicular, the tank works up and down an inclined plane; or again, instead of floating straight out of the canal into the tank, the boats may be supported by a suitably shaped truck, running on rails, a wire rope being used to haul them from one reach to another.

When we consider that the early canal builders performed their work entirely without the aid of such mechanical appliances as are used by the canal builders of our own time, their works must have for us a new magnitude. Canal making is a science that has so completely changed in modern times that one may be excused for wondering what the great pioneers of canal engineering would think if their shades could revisit the earth and witness the operations of the canal builder of to-day. The burly navvies' labours are assisted by steam giants, with irresistible jaws, which remorselessly tear a passage through the earth. Stubborn rock, which used to take a long time to excavate by hand, is now drilled by machinery as easily as though it were chalk; and for a dozen other purposes the modern engineer uses mechanical appliances undreamed of by his predecessors.

Perhaps the most interesting of the marvels that the engineer has brought to aid him in the task of making earthworks is the steam navvy, or, as it is sometimes called, the steam shovel, or excavator. Steam navvies are made of many patterns, but in principle they are all alike, and all consist of a strong, bucket-like receptacle, which is forced against the face of the material to be excavated by the powerful leverage of a steam engine. Sometimes this leverage is obtained by suspending the bucket from the jib of a crane, a chain pulling it upwards into the material, and a steel arm being used to hold it tightly against the working face; in other patterns the bucket is fixed to one end of a great beam, the beam itself being moved by chains.

Steam navvies are very powerful, and the great bucket that takes the place of the spade of the human navvy can dig and hold two or three tons of material at a single cut. When it has been driven upwards through the face, the bucket is swung round, and empties its contents into trucks placed in readiness underneath. Surely it is a wonderful invention that can cut away a couple of tons of clay in half a minute, and can do in a single day as much excavating as eighty able-bodied workmen can do! The steam navvy moves on wheels of its own, which run on rails set 10 or 12 feet apart. It is a very massive and unwieldy machine, often weighing as much as 60 tons, and constantly being subjected to enormous strains. When working in clay or other soft material a bucket is provided with a sharp steel cutting edge; but when it is used for clearing away rock that has been broken up by blasting, a bucket fitted with rows of formidable-looking teeth is used. The bottom of the bucket is hinged, and when it has been filled the driver pulls a cord that releases a catch, and the bottom opens and discharges the contents. The bottom flap is so balanced that, as soon as the bucket is lowered to start a fresh cut, it automatically shuts itself.

Some kinds of excavators are made after the pattern of dredgers, and cut downwards instead of sideways, as in the case of the ordinary steam navvy. A great many buckets are attached to an endless chain, and scoop out the ground as they pass along the under side of a curved girder, which is lowered little by little as the channel becomes deeper. Such dredger-type excavators as these are very useful in soft materials—alluvial mud, sand, or soft clay—but they have not the great strength of the ordinary steam navvy, and cannot tackle rock and hard materials so successfully.

It is a maxim of the earthworks engineer that the rate at which excavation can be carried out depends on the rate at which the excavated material can be removed; and you will see at once that the steam navvies must come to a stop if there are not enough trucks to carry the spoil away. The arrangement of the lines on which the spoil trucks run, and the ease with which the latter can be hauled to the spoil banks, are matters that require the engineer's very careful consideration. The earth and rock dug out at one place are used at another for making dams or embankments; and one of the views with which the route of a canal is selected is that of making the amount of cutting as nearly as possible equal to the amount of embanking.

At the side of the steam navvy stands a train of empty spoil trucks, and as the bucket of the navvy is swung round and emptied into one truck the train moves forward one truck length, so that the next empty truck is in position to receive its load. Sometimes two or more navvies will feed one train of trucks. As soon as all the trucks are filled the train is hauled off to the spoil bank, which may be 20 or 30 miles away, and an empty train is brought up to take its place. The empty trains and the full trains have to be kept on separate lines, and a canal in process of construction presents a vista of railway tracks, running along the bottom and on ledges cut in the sides; so many lines are there that one might almost believe that he looked down upon a great goods depot. The loaded trains on their way to the spoil banks have to be kept out of the way of the empty ones returning to the scene of excavation; and a tremendous race is kept up between the steam navvies and the trucks serving them.

There are so many wonderful canals in the world that it would be quite impossible even to mention the more important of them. Let us therefore take one or two of those of which all have heard, and tell the stories of their making.

Everybody has heard of the Isthmus of Suez and of the great canal that was cut through it in the middle of last century; but few, probably, of the younger generation at all events, know what a great undertaking the building of the canal was, or what a storm of jealousy and bickering its proposal raised among the engineers and diplomatists of Europe. To start right at the very beginning of the history of the Suez Canal, we must carry our minds back to a very early period in the history of Oriental civilization. Some six hundred years before Christ the Isthmus of Suez was bisected by a great canal, over which the ships of Egypt and Persia journeyed from the Mediterranean to the Red Sea. It gives us some notion of the state of civilization to which the ancient Egyptians rose, and of their capabilities as engineers, to read that the canal was 92 miles long, its width over 100 feet, and its depth about 20 feet. Of its total length about 60 miles were excavated by hand, the remainder passing through natural lakes and depressions. The canal had an existence lasting for about twelve hundred years, being finally abandoned in 767 A.D. Many times it became silted up with sand, and as often as this happened it was re-dug and improved by one king after another, until at last either indifference to its utility, or the perpetual warfare that was waged in its vicinity, or perhaps the persistence of the sand itself, caused it to fall into disuse.

It is a long jump from the "Canal of the Prince of the Faithful", as the canal just described was called, to modern times, and to the proposal of the Suez Canal as we know it to-day. The attention of engineers, financiers, and diplomatists was first turned to the Isthmus of Suez after the occupation of Egypt by the armies of Napoleon Bonaparte, when, with the object of finding out the feasibility of building a new canal, Bonaparte caused a body of engineers to survey the isthmus. Nothing came of the survey: but with the development of European intercourse with India and Australia, the growing need for a shorter route to these countries made itself felt more and more as the years went by; for you must remember that until the opening of a railway from Alexandria, on the Mediterranean, to Suez, on the arm of the Red Sea called the Gulf of Suez, passengers, mails, and merchandise had to go round the Cape of Good Hope—a journey that occupied ninety days by steamer, and four months or longer by sailing vessel. This railway formed part of what was known as the overland route to India; it was not opened until 1858, and was the outcome of British jealousy of the French scheme for a ship canal through the Isthmus of Suez. Of course, a railway could never have taken the place of the canal; for, although the railway enabled passengers who were in a hurry to get over their journeys—and you must know that fifty years ago people did not hurry quite so much as they do now—to save two or three weeks by making use of the overland route and joining the boat at Suez, the distance travelled by the boat itself was as great as ever, and the voyage cost as much in coal and wages and wear and tear as if there had been no railway.

In 1847 the question of whether a ship canal could be cut across the isthmus was seriously taken in hand, and a commission of engineers, representing France, Britain, and Austria, was appointed to survey the route and report on the feasibility of the plan. The commission's report was unsatisfactory, and nothing was done. Six years later Mr. Robert Stephenson, the famous English engineer, and M. Talabot, a Frenchman of equal distinction, were again asked to go into the practical difficulties of the question. M. Talabot was in favour of the canal scheme; Mr. Stephenson was strongly against it. The Englishman urged that as an engineering undertaking it was impracticable, and that as a commercial venture it could never pay; and his principal grounds for his disapproval of the scheme were the necessity for building an extensive harbour, protected by a heavy breakwater, at the Mediterranean end of the canal, and the fact that the engineers would have no better foundation to build upon than the soft mud brought down by the Nile. As presented by Mr. Stephenson, the idea of cutting a ship canal through the burning, waterless sands of the isthmus, where rain falls only once in two or three years, and where the sand would silt up the canal as soon as it was dug, seemed fantastic enough; but in the following year there appeared a new and formidable advocate of the Suez Canal, in the person of Ferdinand de Lesseps, a French officer in Egypt, who was destined to become one of the most famous actors in the world's international quarrels of the nineteenth century.

M. de Lesseps planned a canal running in a straight line from a place called Tyneh, on the Mediterranean, to Suez. This canal was to be 330 feet wide and 20 feet deep, and was to be provided with a sluice-lock at each end to guard against the scouring action of the tides. The Frenchman's scheme was laughed to scorn by some of the most eminent engineers of the day, particularly by those in Britain, for our engineers were jealous of the French spirit of enterprise that was showing itself in Egypt, and our politicians were not slow to show equal dislike for the scheme. The colossal nature of M. de Lesseps's plan gained for him immediately a wide notoriety, although not altogether an enviable one. He proposed to build at each end of the canal an enormous artificial harbour. That at Tyneh was to be carried out 5 miles into the sea, in order to obtain a permanent depth of water of 25 feet, on account of the enormous quantity of mud—some 20,000,000 or 30,000,000 cubic yards—that the Nile pours out annually. Millions of cubic yards of good stone were required to build this harbour, and there was not a stone fit for use except at a very great distance away—nothing, in fact, but the limitless sand. Small wonder that people laughed at the scheme!

But the need for making the world smaller—for adding a little bit to the sea by taking away a little bit of the land, so that men might get around it in less time—was making itself felt; and while this was happening people began to think that it was very stupid to quarrel as to who should make the canal, since all nations would have an equal chance of sharing the benefits that it was intended to create: and the question was again taken up, another international commission being appointed. The result of this commission's deliberations was that a canal was considered practicable, and M. de Lesseps's scheme, somewhat modified, the best one to adopt. It was therefore decided to construct the canal; a company was formed, most of the money being obtained in France, and operations were commenced at once. De Lesseps was made engineer-in-chief, and nearly all his assistants were of his nationality, so that the Suez Canal must be regarded as a French undertaking; indeed, the French share with the British the reputation of being the finest engineers in the world, and as canal builders they are certainly unequalled.

De Lesseps's original idea for a Mediterranean entrance at Tyneh was abandoned in favour of one at Port Said, a village situated on a narrow neck of land at the eastern end of the Nile delta. This neck of land is something like the extraordinary Chesil Bank connecting Portland Isle or Bill with the Dorsetshire coast, and encloses a large shallow called Menzaleh Lake. It was also decided that, instead of a straight course, as at first proposed, the canal should follow a slightly circuitous one, so as to make use of some natural lakes, and in this way reduce the amount of excavation necessary. Thus, of the canal's total length of 95 miles, only about a third was cut out of the solid sand and rocks of the desert.

One of the most interesting features of this prodigious undertaking was the construction of the harbour at Port Said. I have already said that the entrances to the canal had to be protected; and you will remember that de Lesseps's first plan provided for an enormous harbour at Tyneh, and that people laughed at him because there was no stone within a great distance wherewith to build that harbour. Port Said did not require such extensive works as Tyneh would have done, but there were, none the less, large breakwaters to be built; and, of course, the absence of stone was a difficulty that still applied. It was, however, a difficulty that did not trouble de Lesseps very much. Since there was no stone available, he resorted to the simple course of *making it*—or, rather, of making a substitute for it.

Although there was no stone there was any amount of sand—a good deal more, indeed, than anybody cared about—and sand, you know, is the principal ingredient of concrete, so a great works was set up at Port Said for making huge concrete blocks. By pouring into wooden moulds a liquid mixture of sand and cement made of hydraulic lime an excellent artificial stone was made, better able to resist the destructive action of the sea water than most kinds of natural stone. (Indeed, concrete blocks are now generally preferred to stone for building piers and other submarine works, on account of their greater durability and smaller cost.) The blocks used at Port Said weighed 20 tons, and took several months to set and harden before they could be used. When they were ready, a giant travelling crane took charge of them and laid them tenderly in their places. Two breakwaters had to be made, one of the length of 7000 feet, and the other of 6000 feet. The channel between them, forming the entrance to the canal, is kept constantly dredged; and the dredgers are generally at work somewhere or other on the canal, and always will be so long as it exists.

While the canal works were in progress the desert on either side of the route presented a spectacle such as had never before been witnessed there, and is never likely to be witnessed again. From an insignificant village Port Said grew in a few months to a town of twelve or fifteen hundred inhabitants. Engineers, contractors, administrators, solemn Arabs, cunning Turks, whites from every country in Europe, Greeks and Albanians, Frenchmen, Italians, Englishmen, jostled each other at every turn; and a traveller who visited the works said, on his return, that the canal could never be made until the international rabble had been cleared out of the way! In the desert of the isthmus the change was still more extraordinary. Along the line of the canal the sandy solitudes were ruthlessly invaded by armies of swarthy Arab labourers. On a roughly laid track panting locomotives brought up weird-looking dredgers and excavators. A spectator gazing on the rows of Arab tents might have thought that they were the encampment of an army — as, indeed, they were, though not of warriors. And wherever the tents were pitched, near them there sprang up a town, as if transplanted from the plains of France to the plains of Northern Africa; a town with its houses, its shops, its cafés, its hotels, and perhaps its theatres, and thronged with the dapper, irrepressible, cigarette-smoking canal builders, and their wives and families.

After leaving Port Said the canal passes through Lake Menzaleh, a salt-water shallow through which a channel had to be dredged. On either side of this channel the engineers raised an embankment 15 feet high, extending for the whole distance across the lake, some 20 miles. Here, perhaps, it may be as well to explain that, although the Isthmus of Suez is a sandy desert, it is not all on one level. One commonly thinks of a desert as a perfectly flat expanse of land; but it is not necessarily flat, and the land through which the Suez Canal passes was lumpy enough to entail a vast amount of cutting and embanking. After leaving Lake Menzaleh our ship pursues a straight course for 11 miles, through cuttings of various depths, until it reaches another lake. Passing onwards, there are other 11 miles overland, the depth of some of the cuttings here being over 70 feet; then there is another lake to be crossed, and shortly after the greatest work of the engineers comes in sight, for we enter the cut that crosses the Serapeum plateau, where the inexhaustible sand gives place for a few miles to hard rock. As the plateau is, on an average, 40 feet above the level of the sea, you can readily understand what a terrific task it was to carve a passage through it, and what enormous quantities of explosives were necessary to loosen the rock before it could be removed. The deepest cutting on the whole canal is 80 feet below the surface of the land; and the brain almost reels in the attempt to gauge the magnitude of the work that de Lesseps and his colleagues set themselves, when they started to dig to that great depth a colossal trench, from 150 feet to 300 feet wide at the top, and 75 feet wide at the bottom. How the canal builders, from the highest to the lowest, must have wearied of the unending sand when, after months of feverish labour under a broiling sun, they looked upon their work, and saw that what they had accomplished was but an insignificant fraction of what they had to do!

The canal was formally opened, with great pomp and ceremony, in November, 1869. It had cost nearly £20,000,000 to build, and had engaged the energies of some 25,000 workmen during a period of more than ten years. There were many people in those days who regarded the construction of the canal as a great waste of money. What a lot could be done with £20,000,000! they said—quite overlooking what a lot *had* been done with that sum. The canal would be of benefit, perhaps, to a few steamship companies, they thought, but it could never pay; and their attitude towards de Lesseps's work was very much like that of the historical old lady who, on being told that the ancient Incas of Peru built marvellous roads, and established on them such an elaborate system of point-to-point messengers, or runners, that it was possible for fish caught one day on the Pacific coast to be eaten the next day at the capital, some 300 miles inland, said, in surprise: "Dear me! how fond of fish they must have been!" A fish supply was not the object of the Incas' great roads, and the Suez Canal was not cut for the benefit of a few, but for the benefit of the whole world.

Truly, the narrow streak of water trailing from sea to sea across the parched Isthmus of Suez seems a small thing to have cost £20,000,000; but its builders' service to mankind takes on a new importance when we come to realize that the infinitesimal addition that they made to the waters of the world meant the avoidance of another streak of water nearly 5000 miles long. To be more explicit, let us say that the distance from London or Hamburg to Bombay is, by the Cape of Good Hope, 11,230 miles, and by Suez only 6330 miles; and that, thanks to the Suez Canal, Europe and India and Australia are brought nearer together by *three weeks*. The Forth Bridge enables people to cross the rough waters of the Firth of Forth without any hindrance from their turbulence; the Severn Tunnel shortens the journey to South Wales by, at most, an hour or so; the great Alpine tunnels have reduced hours to minutes: but how much greater than all these advantages is the saving of time and money afforded by the Suez Canal!

In 1870, the year following the opening of the canal, 491 ships passed through the canal; in 1871, 765 ships passed through. In 1910 this number had increased to 4533, which means that in that year more than 12 ships passed through every day, on an average. More than 50 per cent of these ships carried the British flag. The gross receipts in the year 1909 were more than £60,000,000, three times the original cost of the canal—pretty good for an undertaking that people thought would be a commercial failure! But perhaps I can give you the best idea of the immense value of the canal by mentioning that four million pounds' worth of shares which the

British Government bought in 1875 are now worth about five times more than was paid for them. The traffic passing through the Suez Canal is still, in volume, the heaviest for any canal in the world. In 1923, 4621 ships passed through, of a gross tonnage of 22,730,000 tons. But these figures were nearly reached by the Panama Canal, which carried 4000 ships, of a total of 18,600,000 tons, and it is likely enough that within a comparatively short time the wonderful canal linking the Atlantic and the Pacific will be dealing with tonnage of a volume unheard of in the history of the Suez Canal. The latter is old, and feeds established trade routes, while the Panama Canal is destined not only to encourage divergence from existing routes, but also to develop entirely new markets.

Among the ship canals of the world, those that connect the Great Lakes and rivers of Canada are of high importance. The big lock—900 feet long—on the Sault Ste. Marie Canal (commonly pronounced *Soo*) passes in a year a much larger number of ships than the Suez Canal, though the ships themselves are of a different kind and of a less tonnage. They are the long, narrow "whale-backs", typical of the Great Lakes, that take enormous quantities of wheat and iron-ore between the Lake ports of Canada and the United States. There are two St. Mary's Fall or "Soo" canals connecting Lake Superior and Lake Huron, one Canadian and the other belonging to the United States, and though both have cost some millions of money, their economic value to the two countries concerned has been incalculable. Important manufacturing towns like Buffalo and Duluth, and other industrial centres on both shores of the lakes, owe much of their prosperity to the cheap transport facilities provided by the St. Mary's Falls Canals.

They were wise statesmen and bold who planned the canals of Canada and found the money to build them, for though their total length is under 300 miles, and though they are not designed for the greatest ships afloat, they render navigable for vessels of considerable tonnage more than 3000 miles of inland water. The Welland Canal does for Lakes Erie and Ontario what the "Soo" Canal does for Lakes Superior and Huron, and ships from the ports on all the Great Lakes can reach the Atlantic without breaking bulk, a distance of some 2300 miles, and a difference of hundreds of feet in level.

It is unhappily the case that of all great countries Great Britain is the worst provided with canals. France, Germany, Holland, Belgium, Denmark, have spent and continue to spend very large sums on the maintenance and improvement of their canals, while we have been content to sit still and do nothing.

Great as is the strategic value of the Kiel Canal, which is also called the North Sea or Baltic Canal, its commercial value is infinitely greater. To appreciate thoroughly its vast importance, not merely to Germany, but to all the nations of northern Europe, we must look at the map. From it you will see that, apparently, the only way to the Baltic Sea is by going round the perilous coast of Denmark —a coast that is one of the great wreck grounds of the North Sea. If you now look more carefully along the western coast line of Germany you will find the mouth of the river Elbe, and, following the river inland just a little way, you will next find a place called Brünsbüttel. Here is one entrance to the Kiel Canal, which you can trace across the province of Schleswig-Holstein to the great port and naval base from which the canal takes its name. The canal has a total length of 64 miles. It is 220 feet wide and over 30 feet deep, and is thus available for the passage of very large ships. It took eight years to build, eight thousand men were employed to build it, and it cost about £8,000,000—a trio of eights which it is easy to remember.

While the Kiel Canal has only shortened the journey between London and the Baltic by some 230 miles or so, it has a direct influence on the daily life of every one of us, although we may never go to the Baltic, or even think of it; for these two hundred odd miles knocked off the distance that ships have to travel on their passages between the North Sea and the Baltic Sea mean so much of the cost of carriage knocked off also. This, in turn, means that the commodities that come to us from the Baltic Sea reach us so much the cheaper, on account of the enterprise of our cousins on the other side of the "puddle", as the treacherous North Sea is called by those who make use of it, on account of its shallowness; and that the wheat from the plains of Hungary and Russia, the timber that is shipped from Danzig and Stettin, the hides and tallow from Riga, cost us a little less, owing to the shortening by this great canal of the distances they have to travel.

Although most of the British canals are more or less derelict, or else useful only for small barge traffic, there is in England one canal that is numbered among the great ones of the world. This is the Manchester Ship Canal, which has enabled Manchester, although it is more than 30 miles from the coast, to attain the fourth place among the ports of the United Kingdom. The wonderful canal that accomplished this for a city situated so far inland was opened for traffic in 1894, having taken seven years to build. It is only 35 miles long, but its cost was hugely in excess of that entailed in the building of the Kiel canal, and amounted to the enormous total of £15,168,000. Ships of 10,000 tons can pass through it, for it is 26 feet deep, and 150 feet wide at the bottom.

You may wonder why the Manchester Ship Canal cost so much, compared with the others of which we have spoken, especially as it is shorter than either of them. The Kiel Canal cost, roughly, £125,000 a mile, the Suez Canal about £200,000, while the Manchester one cost more than £400,000 a mile. There were several reasons for the great cost of the English undertaking. Both the Suez and Kiel are sea-level canals, and although there are sluice gates at each end, they are not used for lifting the ships up, but only for keeping in the canal waters when the tides go down. But the Manchester Ship Canal rises some 60 feet on its journey from the Mersey, which it leaves at Eastham, a few miles above Liverpool, to the great docks of the Cotton City, and to accomplish this rise great locks had to be built. There are five sets of locks altogether, and there are two locks, arranged side by side—one 600 feet long and 65 feet wide, and the other 350 feet long by 50 feet wide—in each set, except in the case of the last locks, at Eastham, where there are three.

The locks cost a great deal of money, as you can imagine, from the particulars that I have just given as to their size; but they alone did not account for anything like the total cost of the canal. In the first place, the company that proposed to build the canal had a great deal of difficulty in persuading Parliament to give it powers to do so (for you must know that no canal, or railway, or other great work of public usefulness can be built until it has been sanctioned by a special Act of Parliament, passed after the Government has satisfied itself that the proposed work is really likely to be useful, and that its promoters are capable of carrying out what they undertake to do). In the case of the Manchester Ship Canal, Parliament was very reluctant to grant the necessary sanction, with the result that the promoters of the canal had to pay an enormous sum in preliminary expenses—more than a quarter of a million sterling, in fact—before a single step could be taken towards its construction. Then, to add to the expense of building, the engineers suffered serious reverses in their encounter with the forces of nature, and there were a number of accidents, of which we shall presently speak. But neither the locks, nor the parliamentary expenses, nor the accidents that befell the works could altogether account for the immense cost of the canal. What factor remains, by which the abnormal cost can be accounted for?

Perhaps, like Ducrow (of whom you may have heard), you say, or think, "Cut the cackle and get to the 'osses!"—in other words, you may not be much interested in how the cost was incurred; and, as this book is written with a fixed desire to interest you, I shall not invite your displeasure by pursuing this subject much further, especially as it is time that we had another chapter. The answer to my query must be given, partly because it is interesting, and partly because (though this concerns you less) it is important; it is, moreover, an answer that will occur to only the very thoughtful ones among my readers. The Manchester Canal cost the huge total of £15,168,000 because it passes through the most thickly populated district of England. If it had been built almost anywhere else it would have cost less, for the land that had to be bought before it could be made would have been less valuable, and there would have been fewer roads and railways to be carried across it on expensive bridges, and diverted while it was being built. Two existing canals had to be bought up, at a cost of £1,750,000; while the purchase of lands accounted for another million and a quarter.

Some very fine engineering work was entailed in the course of the railway alterations. Altogether four or five lines had to be carried across the canal, and you must remember that big ships pass along it, and it was therefore necessary, whenever a railway or a road crossed the canal, either to carry it on a swing bridge, which could be moved when a ship wanted to pass it, or else on a high-level bridge, under which the canal traffic could pass. In the cases of eight or nine roads that had to be accommodated swing bridges were provided, although in two other cases high-level fixed bridges were used; but swing bridges were out of the question for the railways, as, of course, it would never have done to stop the trains and dislocate the railway traffic while a bridge was swung round to allow a ship to pass. The trains, therefore, cross the canal on bridges that are 75 feet above the water level; and in order that the approaches to these bridges should not be too steep, long and expensive embankments had to be built.

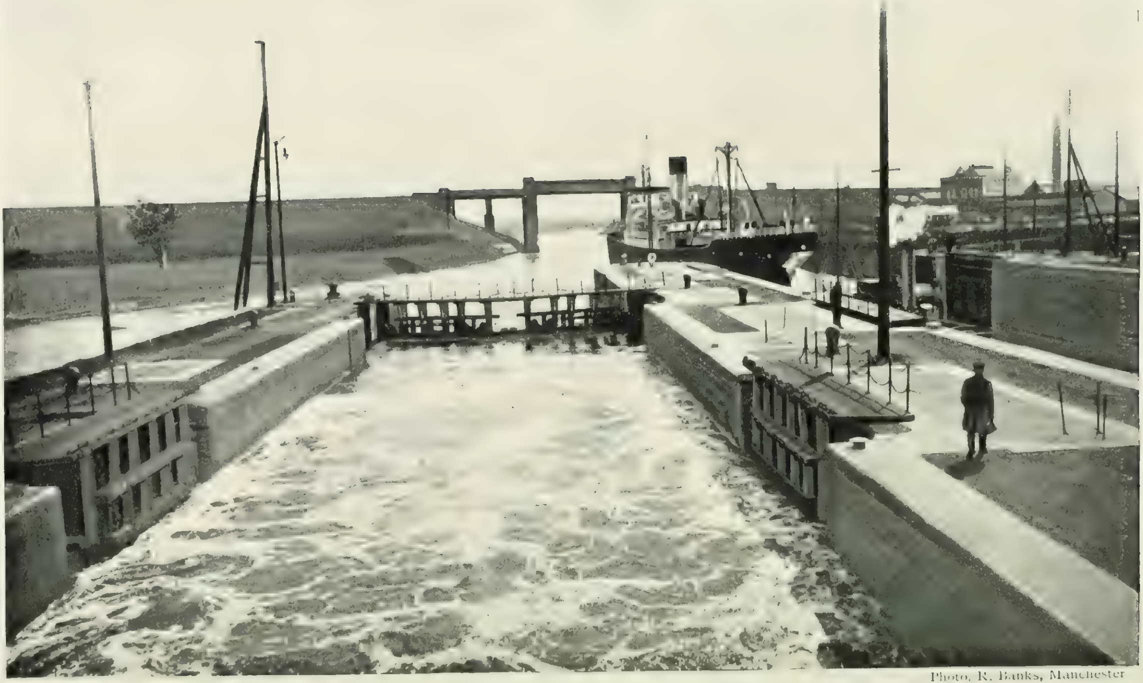
Some of the cuttings on the canal are over 60 feet deep, and pass through material that gave the contractors a great deal of trouble. Near the sea end of the canal soft clay and sand had to be cut through, and when the cuttings had been made they had to be protected in some way. In one place, near Runcorn, a concrete wall, 4300 feet long and 40 feet high, had to be built, the thickness of the wall varying between 22 feet and 16 feet. In another place a great wall of timber piles, more than a mile long, had to be driven, a water jet being used for this purpose. But the most interesting of all the works on the canal is the Barton Swing Aqueduct. Here the Bridgewater Canal, built by Brindley, crosses the Manchester Ship, and the question arose as to how the smaller canal was to be made to pass over the larger without interfering with the level of the former. The answer was found by treating the Bridgewater Canal as though it were a road, and taking the boats on it over the larger canal in a swing bridge. A solid masonry pier was built in the middle of the Ship Canal, on which the bridge carrying the Bridgewater Canal boats could swing round. This bridge consists of an iron trough, over 200 feet long, which can be closed at both ends by swing doors. There are also doors at the ends of the canal, by means of which the waters can be shut off from the aqueduct. When all the doors are open there is, of course, a clear passage along the canal and over the aqueduct; but when a ship wishes to pass under it the doors are closed, and the aqueduct is thus cut off from the rest of the higher canal and is swung round, probably with a barge in it, the towing horse standing calmly by the side on the platform specially provided for him. It is a curious and amazing sight to look up from the deck of a steamer on the Ship Canal at a barge floating in a trough held up in mid-air, and one wonders what the builders of the canal of which the trough forms part would think could they but see it.

CHAPTER IX

The Story of the Panama Canal

It is a long journey from the eastern hemisphere to the western, but thither we must sail in order to learn something about the greatest engineering undertaking of modern times, and, indeed, of all times; for we are going to see the Panama Canal in the making, and the Panama Canal must rank among the biggest of the world's big things. The great pyramid at Gizeh, the vast canals of the Chinese, the mighty roads of the Incas will remain among the wonders of man's handiwork long after our history books have forgotten the Forth Bridge and the Simplon Tunnel; but greater by far than any of these is the Panama Canal—a narrow waterway only a few miles longer than the Manchester Ship Canal—a waterway that has cost a hundred million pounds, that has killed men by the hundreds, that has brought ruin and poverty to thousands of happy homes.

The Panama Canal represents the greatest notch that man has ever attempted to cut on the face of Mother Earth. For fifty years men of many nations, aided by the largest and most powerful machines, have been scraping away at the hills of



Photo, R. Banks, Manchester

THE MANCHESTER SHIP CANAL: IRLAM LOCKS AND RAILWAY VIADUCT

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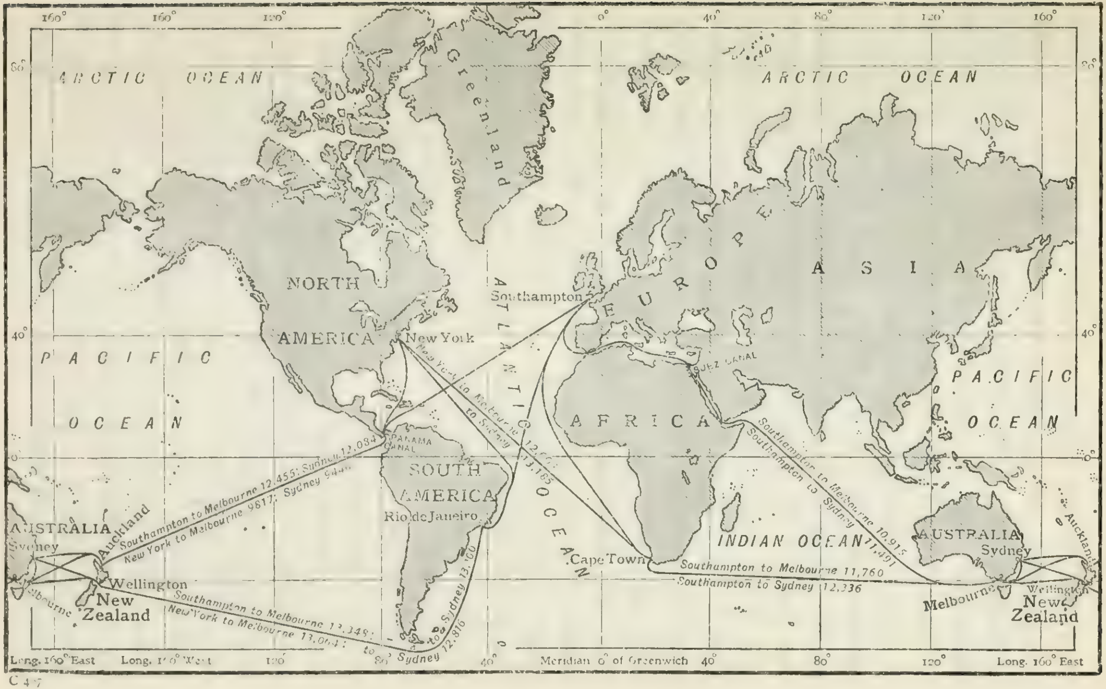
the narrow isthmus that by a whim of Nature prevented North and South America from being two great islands; and the work is barely finished! This is not a history book, but it is impossible for us to understand thoroughly what is now completed on the Isthmus of Panama unless we know something of what has been done during the fifty years in which armies of workmen, sometimes large and sometimes small, have been endeavouring to cut through it, and we must therefore skim lightly over that period. First of all, let us get out the atlas again and see what the Isthmus of Panama is like, and what is its relation to the rest of the world. We find that the territory of the Republic of Panama, which occupies the isthmus, runs roughly east and west, and forms a narrow, S-shaped strip of land, separating the Republic of Costa Rica, in Central America, from the Republic of Colombia, in South America. Looking first along the north, or Atlantic coast, you come to the port of Colon, at the mouth of Limon Bay; looking next along the south, or Pacific coast, you will soon find the town of Panama. It is between these two places, Colon and Panama, that the Panama Canal was built, and was in process of building for so many years. So far as we can see from the map, it does not at first appear as though it would be a very difficult matter to cut through that narrow strip of land; but if you look more closely you will see that running along the isthmus is marked a range of mountains, called the

Cordilleras, and, also, that a river—the Rio Chagres—after following a tortuous course across the isthmus, empties itself into the Atlantic Ocean, which is here called the Caribbean Sea. The Cordilleras have to be crossed by the canal, and although at Culebra, the point of crossing, the range has diminished in height to little more than 500 feet, and is, in fact, scarcely worthy to be called a hill, yet it, and the Chagres River, whose basin the canal follows, are mainly at the bottom of the difficulty of making the canal, and have been principally responsible for the enormous cost of the work—a cost far greater than the costs of the Suez, Kiel, and Manchester Ship canals put together—and for the weary time that this work has taken to execute. Why the Cordilleras hills and the Chagres River are responsible for all this we shall see presently. Just now, while we have the atlas before us, let us see what the canal is going to do; that is, why ships are expected to pass through it in such great numbers as will be necessary if it is to earn a reasonable profit on all the millions that have been spent.

The object of all canals is the shortening of distances by sea between one port and another, and the expansion of old markets and outlets for products and the opening up of new ones. The Panama Canal is no exception to this rule. We had something to say about the shortening of trade routes by the opening of the Suez Canal; and you know how much nearer India and Australia were brought to Europe by its



Map of the World, showing the shortening of routes from New York to Australia and New Zealand by the opening of the Panama Canal.

means, because there was no longer any necessity for ships to voyage to those countries via the Cape of Good Hope. Just in the same way the opening of the Panama Canal has brought Europe thousands of miles nearer to the ports on the Pacific coast of America, and has brought the Atlantic shores of America within easy reach of the Pacific shores; while of still greater importance to America is the shortening of the journeys between New York and Japan, China, Australia, and New Zealand, by distances varying from 3720 miles in the case of New York and Yokohama, 3806 miles in that of New York and Sydney, 2650 in that of the same port and Melbourne, to 1600 in the case of New York and Shanghai. Who can foresee what far-reaching effects the canal may not have on the existing trade routes and markets of the world? And who will dare to say that the changes that are certain to come about will not amply repay the United States for the money and the labour it has devoted, and is still devoting, to the greatest enterprise the world has ever seen?

And now for the history, without knowing which we cannot properly understand the full magnitude of the task that the makers of the Panama Canal had set themselves to carry out. To trace the history of the projects that have had for their object a sea route across America would fill a volume; and, though it would make a volume of absorbing interest, we cannot even touch upon it here. Suffice it to say that the discussion of a canal across the Isthmus of

Panama has been going on for centuries, and that some twenty or more different schemes have been put forward. We know that Columbus believed that there must be an opening severing the isthmus, and that, for very obvious reasons, he failed to find one. In the sixteenth and seventeenth centuries several bold and long-suffering explorers set sail for the East Indies, shaping their courses westwards from Europe, in the vain hope of discovering a passage across America. Dearly would I like to sail again with you those desperate voyages of the men who added the New World to our maps, to face in imagination their perils of shipwreck, pestilence, and battles, to discover once again the treasures of Peru and Mexico; but these things are forbidden, and we must climb down from the romance of adventure to the prosaic dealings of the nineteenth century.

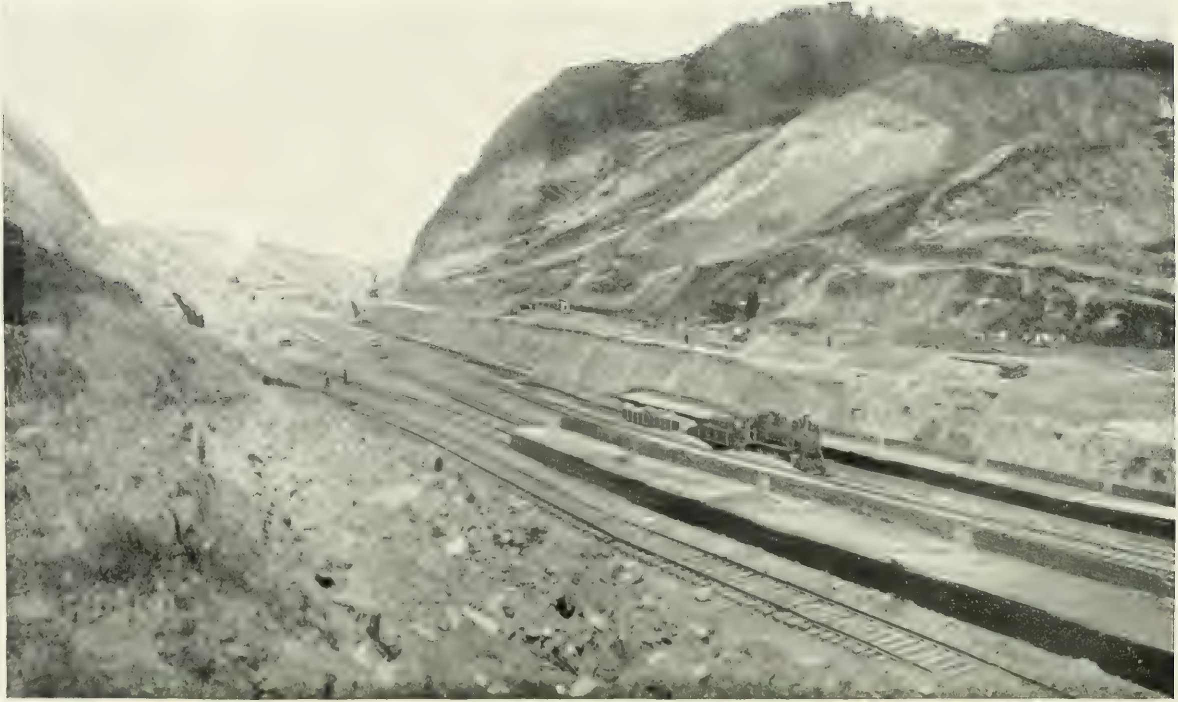
Ferdinand de Lesseps, you will remember, was the great Frenchman who cut the Suez Canal in the face of great obstacles, physical and political, and who cut it successfully. Ten years after the opening of the Suez route, which had in that period shown itself to be a magnificent commercial success, de Lesseps decided to cut a canal across the Isthmus of Panama. In 1881 he called upon the people of France to enable him to carry out his scheme by providing him with the necessary capital, and the people of France, who regarded the engineer as a national hero, literally flocked to his standard with their purses in their hands. About two hundred thousand persons between them took up shares to the value of £16,000,000; and men and machines were immediately sent to Panama, to start the work of cutting the canal. De Lesseps decided that his canal should follow the course of the Panama Railway, an American enterprise that had been completed in 1855; and, what was to have a greater bearing on the subsequent history of his scheme, he also decided that the Panama Canal should be a sea-level canal, like the one he had cut between Port Said and Suez.

Just think what this meant! I have said that the ridge of the Cordilleras, at the point where the canal crosses it, reaches an altitude of 500 feet, and the task that de Lesseps set himself was to cut a passage through this ridge to the very level of the sea. For a distance of 8 miles on the route of the canal a section, known as the Culebra cut, by which name we shall afterwards refer to it, had to be dug out to depths varying from 100 to 538 feet! Utterly ruinous as the project afterwards showed itself to be, and ludicrous as it appears to us to-day, we cannot fail to admire the extraordinary pluck that the facing of such a gigantic scheme demanded of those who dared to undertake it.

De Lesseps and his assistants knew all about the Cordilleras, and planned the Culebra cut before they started on their giant scheme. But there were two factors whose power to hinder their work they did not fully realize. One was the "white death", and the other was the Chagres River. The "white death" had its origin in the thick, white, fever-laden clouds that hung like a pall over the swamps of the isthmus, and covered the hilltops in the rainy season. I have called them fever-laden, and so the French engineers thought them to be, as did also the American engineers who built the railway before them, for the men died like flies in hundreds, and the cemeteries that were established at Colon and elsewhere grew white with gravestones with ghastly rapidity. The loss of life caused by yellow fever and malaria is terrible to read about, and one cannot think without a shudder of the brave Frenchmen and their negro fellow-workers facing frightful odds in the canal zone far away in the fever-racked tropics, ever expecting to be numbered among the thirty or forty whose bodies were daily laid to rest. But, bravely though the workers faced the terrors of disease, they could not resist its demoralizing effect; the result was that the hundreds who died caused smaller loss to the army that invaded the swamps and hills of the isthmus than did the thousands who lived, but were rendered useless for hard toil by an ever-increasing dread of the fever that stalked among them, striking with such a destructive hand. It was not until after the French had abandoned their scheme that scientists discovered that malaria and yellow fever are not caused by the "white death", as the French called the vapours of jungle and swamp, but by different varieties of mosquitoes, which can be destroyed, as we shall shortly see.

The problem presented by the Rio Chagres was of another kind—one that, though it did not attack life, was scarcely less difficult to overcome than disease had been. You will remember that, roughly, the canal follows the course of the Chagres. In dry weather this river is quite an insignificant affair, but after rain it becomes a seething, boiling torrent, overflowing its banks, and flooding the country for miles around. Following the course of the river inland from its outlet in the Caribbean Sea, we find that the valley in which it runs pursues a fairly straight course for about 25 miles to a place called Gamboa, where it turns eastwards at a sharp angle, and thereafter lies nearly parallel with the ridge of hills dividing the isthmus. The manner in which the Chagres affects the canal can now easily be seen. The canal being at sea level, when the trench reached Gamboa—that is, where the river and the canal part company—the canal would be some 70 feet or more below the level of the river, which would thus discharge itself into the canal in a vast waterfall. De Lesseps's idea was to dam the river at this point, and to divert the waters into an artificial channel, in which they were to be carried to the sea at Colon, about 25 miles off. In planning this, de Lesseps went to work without sufficient data to guide him, and the taming of the turbulent Chagres had a great deal to do with the subsequent abandonment of his scheme for a sea-level canal. The great engineer was planning the Panama Canal on the pattern of the one at Suez, but he failed to realize that there were vast and fundamental differences between the two. The Suez Canal was cut through a waterless desert; that at Panama had to be cut through a country offering far greater obstacles by reason of its formation, and which, moreover, is subject to an enormous rainfall, and is watered by a large number of rivers. Just how great this rainfall is may be judged from the fact that on the Atlantic coast of the isthmus, into which the Chagres empties itself, 140 inches sometimes fall in a year, or, say, about four times as much as in London, and this in the few months constituting the rainy season. At Gamboa, where the proposed dam was to be built, the Chagres has been known to rise *35 feet in twenty-four hours*! And the Chagres, although it is the most formidable, is only one of many streams that are liable to be flooded out of bounds in rainy weather. To carry off this vast volume of flood water de Lesseps would have needed to cut a channel almost as large and as costly as the canal itself, while the dam that he proposed was to have the prodigious height of 150 feet!

During the eight years in which the French were at work they had plenty of opportunities for witnessing the fury of the Chagres, which crossed the canal several times between Gamboa and Colon. On these occasions the flood waters spread ruin throughout the partially excavated cuttings over which they swept,



By kind permission of Lt.-Col. G. W. Goethals, Chairman of the Isthmian Canal Commission

THE PANAMA CANAL

A view of the famous Culebra Cut, the greatest work of excavation ever attempted

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completely destroying heavy machinery, and sometimes blocking up the channel with silt and stones. Indeed, the vast amount of boulders and other materials brought down by the Chagres forms, in the words of Professor Kent, "an almost insurmountable objection to the building of a sea-level canal through the Chagres valley".

As time went by it became increasingly apparent that de Lesseps's original estimate of the cost of the canal would be enormously exceeded. In 1888 the expenditure had exceeded £50,000,000. In that year de Lesseps realized that his project for a sea-level canal was impracticable, and he hastily prepared plans for one with locks, in order to reduce the amount of cutting at Culebra hill and to avoid the necessity for the gigantic dam at Gamboa. This alteration was, however, made too late. Hampered by floods, ravaged by disease, faced with excavations of herculean proportions, and finally—a state of matters by no means the least deadly to the prosecution of the scheme—injured by the gross mismanagement and dishonesty of many of its directors and chief officials, the company at last found itself in bankruptcy, and unable to move a step further. "The expenditure was awful — $300,000,000 (£66,000,000) in eight years—that is, more than three times the sum for which the Suez Canal was constructed. The company went into liquidation in 1889. Much had been embezzled. Much, it is said, had been spent in purchasing the silence of voices which would otherwise have been raised against a europeanized canal."[1]

The failure of the "Compagnie Universelle du Canal Inter-océanique de Panama" was the most disastrous financial ruin the world has ever seen—far more destructive in its effects than the historic "South Sea Bubble" of 1711–20, and, indeed, than all the "bubbles" of that period put together. The shares had been taken up, for the most part, by French families of small means, and to the majority of these luckless people, who had flocked to de Lesseps so full of hope for what he was going to do for them and for their country, the crash of the rotten fabric of the great company brought utter desolation.

The canal works, the Panama Railway, and the machinery and plant left by the ill-starred company were bought up by the New Panama Company. The new company immediately set to work to obtain information as to the feasibility of a high-level canal, and came to the conclusion that such a canal would be vastly preferable, and would cost very much less than that originally proposed by de Lesseps. For the next eight years they kept hard at work scraping away at the Culebra cut, maintaining the railway, and keeping in order the valuable plant and machinery.

It must not be supposed that the French had done nothing towards the building of the canal. It is true that, in the eight years in which they were in occupation of the isthmus, all they could show for the millions they had sunk was only about a fifth of the total excavation necessary to complete the canal; but the little that had been done—we use the word only in relation to what remained to be done—was done thoroughly well: and the engineers afterwards at work on the isthmus were full of praise of the soundness and ingenuity of the Frenchmen's work. Also, it must be remembered, the route to be followed by the high-level canal was to be practically the same as that of the sea-level one that had been commenced, so the French had paved the way for those who were destined to follow.

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[1] Vaughan Cornish, *The Panama Canal and its Makers*. Fisher Unwin, 1909.

In 1904 the United States Government bought up the works and property of the New Panama Company, ratified a treaty with the Republic of Panama, giving it control over the canal "zone", and established an "Isthmian Canal Commission" to take charge of the construction of the canal and everything connected with it.

The first thing that the United States did was to make the isthmus fit for men and women to live and work in. By this time yellow fever and malaria had been traced to two varieties of mosquitoes, called *stegomyia* and *anopheles* respectively. This discovery, which has had results equal in importance to the greatest of modern times, was made during the researches of Major Ronald Ross, of the medical service of the Indian Army. The United States

Commission established a Sanitation Department, and vigorously set to work to stamp out completely the dreaded fevers by annihilating the mosquitoes. The towns and villages lying along the route of the canal were taken in hand first, and cleansed thoroughly and systematically, to the intense astonishment of the inhabitants. Water supplies and systems of drainage were carried out, and after this Masters Stegomyia and Anopheles were attacked. The manner in which the Sanitation Department undertook this warfare is extremely interesting. The larvæ of the mosquitoes are deposited in stagnant pools, ditches, and marshes, and the insects cannot fly more than a few hundred yards from the places where they are born. The officials therefore drew imaginary boundary lines, as it were, between that part of the isthmus across which the canal was being built, and in which the workmen had their homes, and the jungle on either side. Within this boundary they filled up every pool of stagnant water, and covered with oil every drain and ditch and every inch of swamp in which the mosquitoes might be expected to breed. Pipes were laid across the isthmus, and through these oil was pumped. Taps were fitted at frequent intervals by means of which travelling oil tanks could be filled, these in turn being emptied into the ditches and pools by special gangs of men. All swampy ground was carefully drained and oiled. This in itself was an enormous business, and for their protection while it was being done, the men were made to dwell in houses and bungalows having their windows, doors, and shutters covered with fine copper gauze, through which the insects could not enter. Isolation hospitals and infirmaries were built, and the huge army of workmen—there are forty thousand men of all grades now at work—and their wives and families were vaccinated on their arrival in the canal zone.

Nowhere in the world probably were there seen such strange towns as those in which the workmen were housed. In Japan houses are often made of paper on bamboo frames, and in other countries, where earthquakes are an ever-present danger, dwellings are made of plaster or mud; the Laplander and the Eskimo make their huts of snow; but the canal zone on the Isthmus of Panama was the only place where every opening in every building was covered with copper gauze. The Sanitation Department of the Canal Commission, under the leadership of Colonel Gorgas, had made the deadly swamps of Panama not merely fit to live in, but very healthy to live in; and but for the Department's energy and perseverance, the completion of the Panama Canal might never have been possible.

Writing of the life on the Isthmus in the *Times* of December 27, 1910, a special correspondent of that journal presents an astounding picture, showing how the workers on the canal belong, body and soul, to the United States Administration. He says: "The community of the Canal zone, consisting of nearly forty thousand workers, together with their families, of many different nationalities, making up a somewhat curious and interesting aggregation of humanity, is entirely under the management of the United States Government. These people are not only employed and paid by Uncle Sam, but he furnishes them with houses to live in, sells the occupants their food, and supplies all the workers with rations. Government bricklayers, plasterers, carpenters, paperhangers, and painters go from place to place in motor cars, which run on the innumerable railway tracks, for the purpose of keeping the houses in repair and the rooms clean and cheerful. If an employé, or his wife, or his children should be taken ill, Government doctors attend them free of charge. Government inspectors see that the grass is cut in the vicinity of the houses, that the rainfall runs off briskly, that there is no stagnant water anywhere which will enable mosquitoes to breed, and that every possible precaution is taken to prevent the spread of tropical diseases. As a result, the isthmus has become a healthy place, where children may be reared in safety, and where men and women from northern climes may live with perfect comfort and freedom from risks. It is impossible to speak too highly of the sanitary work that has been carried out under the guidance of Colonel W. C. Gorgas. This has made the cities of Colon and Panama, and indeed the whole Canal zone, healthy places in which to live and work. In any praise accorded to those in charge of the Panama Canal the

Sanitary Department is entitled to a good share, for without the feeling of security which the excellent hygienic conditions inspire no such efficient progress could possibly have been made. . . .

"The United States Government also manages the hotels; it has built and conducts clubs, and furnishes amusements and recreations at a reasonable cost for its employés, while in every way it looks after the health and comfort of all classes of workers and their families. There are some spacious modern hospitals for the sick, quarantine stations located on picturesque islands for those coming from plague-stricken ports, and a pretty seaside resort a few miles down the bay, at the Pacific end of the Canal, where those who feel a little 'seedy', or who are becoming convalescent from an illness, are sent by Uncle Sam to enjoy the sea breezes, and to regain their strength. . . . If there is anything that the United States Government does not manage—including the editing of an interesting newspaper—in the Canal zone, my sojourn of ten days at Panama failed to reveal it." And this is in a region where, a few years ago, there existed only a few insignificant towns, surrounded by impenetrable jungle and ghastly swamps!

And now let us take a trip through this wonderful canal in a ship approaching from the Atlantic. In order to make what follows quite clear, and to avoid the confusion that might arise from the repetition of a number of strange names, let us say at the outset that the canal is divided into three main divisions. The first of these, called the Atlantic division, extends from a point in the Atlantic Ocean about 1 mile outside Colon harbour to Gatun, where the second, or Central, division is entered. This stretches practically across the isthmus, covering 31½ miles between Gatun and Pedro Miguel. The third, or Pacific, division, is 11 miles long, and extends from Pedro Miguel to a point 8½ miles out in the Pacific Ocean. The total length of the Canal from deep water in the Atlantic to deep water in the Pacific is just over 50 miles.

Our ship, then, approaching from the Atlantic, enters the deep buoyed channel that has been dredged in Limon Bay, and slows down for the 7-mile journey to Gatun. Now the engines are rung off and we are taken in charge by electric locomotives, for we are about to enter the great Gatun Locks, which will lift us 85 feet to the level of Gatun Lake. When the United States Commission finally abandoned de Lesseps's idea of a tide-level canal (an idea, we ought to explain, that is still held by many engineers to have been thoroughly sound, in spite of its expense), they had to decide on the best plan for a high-level canal. De Lesseps, you will remember, proposed to dam the River Chagres at Gamboa, where it turns off at right angles from the course of the canal, and where it would be, roughly, about 70 feet above the level of the sea, and, of course, of the canal. The Americans decided that the level of water *in the canal itself* should be 85 feet above sea level, the bottom of the canal being 40 feet above sea level. It was necessary therefore to build a series of locks to lift the ships to the canal and lower them to the sea.

The gigantic steel gates of the first lock at Gatun open to admit our ship, and as we pass in, the 30-foot walls towering above us completely shut out the world. It is not for some eight or ten minutes that the water will have risen sufficiently to enable us to take a view of the locks. They are truly enormous. They are built in pairs, side by side, with a wall 60 feet wide separating them, so that ships going in either direction can pass through at the same time, and so that if one lock should be out of repair, it will not seriously affect the carrying capacity of the canal. There are three of these pairs of locks, one above the other, and they are large enough to hold comfortably a ship 1000 feet long. Each is 110 feet wide.

Enormous power is available from the water pouring over the sluices, and turbines generate the electricity by which the lock gates are worked. The end gates open outwards like doors, but the intermediate gates slide transversely into the lock walls. Gates of this kind divide the locks into several smaller locks which are used when the ship to be raised or lowered is not of sufficient size to occupy the lock to its full capacity, thus saving time and water. The gates are gigantic steel structures 7 feet thick, 65 feet long, and from 50 to 80 feet high—each an engineering marvel in itself. They weigh anything from 400 tons for the little ones up to twice that for the big ones, but they can be set in motion by a child by the simple closing of an electric circuit.

A very judiciously designed system of culverts admits the water to the locks. It would be impossible to allow the water to cascade into the great basins as it does into the little river-locks in this country through sluices the boatman often operates for himself: the result would be no mean Niagara—an impressive spectacle, but dangerous to ship and lock. Instead, the water is admitted through a number of tunnels—some of them are the size of a railway tunnel — controlled by electrically-operated sluices. It takes fifteen minutes to fill a lock and about as long to empty it; and as our ship has to pass through three, one leading to the other, to reach the 85-foot level, the locking takes about three-quarters of an hour. We are guided all the time by the four electric locomotives running on rack-rails on the lock walls. No vessel is allowed to pass through the locks under its own power.

Once clear of the locks, we are free to go full speed ahead again. For we are now on the Gatun Lake—a huge artificial lake formed by the taming of the Rio Chagres. No longer is it the turbulent monster the French knew, capable of dealing destruction right and left. Instead, it is no more than a slowly-moving inoffensive current on the bosom of a lake of an area of 164 square miles. I will give you something to compare it with — say the Lake of Geneva. Ah! that is larger than I thought (or you, either)—

223 square miles. And the English counties are much too big, except little Rutland, which is too small. Anyhow, we shall steam over this lake for 24 miles before we reach the Culebra cut.

In order to form the lake two dams had to be built, one at Gatun, which we have just left, and one at Miraflores, whither we are bound. The Gatun dam is one of the marvels of the Panama Canal, and is, indeed, unique in its way, though it is not the biggest dam in the world, as is often claimed for it. However, here are some figures which will give you an idea of the solidity of this monstrous wall: It is nearly a mile and a half long at the crest, nearly half a mile thick at the base, about 400 feet wide at the water surface, and 100 feet wide at the crest. It stands 30 feet above the normal level of the lake and 115 feet above sea level. Writing in *The Times*, Professor Kent said of the dam: "The approach of the high hills to the river at Gatun made an admirable site for the dam, so far as the lay of the land was concerned, but a considerable part of the bottom was of soft material incapable of sustaining a heavy concentrated load, and the substances available were not of the most desirable character, being the excavated material from the Culebra cut and the soft sand and clay mixture obtained by hydraulic dredging from the bed of the Chagres. This difficulty was solved by spreading the base of the dam to the extraordinary width of 1900 feet at the sea level, and giving the sides of the dam a slope of about 10 to 1." Which means that you could drive from the bottom to the top—the vertical distance is 115 feet—quite comfortably on top-gear in any reasonably powerful motor-car.

The dam was built by first laying two "toes" or lines of rock about 1200 feet apart, and parallel to the centre-line of the dam. These "toes" were about 60 feet high and had a very flat slope. The area they enclosed was filled with hydraulic "fill"—that is, by material delivered through pipe lines by suction dredgers on the Chagres River on both sides of the dam. This made an impermeable core about 800 feet thick at the bottom, on which was dumped tens of thousands of tons of rock and "dirt" excavated from the Culebra cut. The upper slope of the dam was protected by a layer of rock 10 feet thick.

The engineers purposely made the Gatun dam enormously greater in width and flatter in slope than was necessary, for two reasons. One was to allay the fears of those who said that a dam in that position was impracticable and unsafe; the other was to do away with the colossal quantities of spoil excavated from the Culebra cut, the disposal of which presented a very difficult problem.

The waters of the huge lake are prevented from overflowing in time of flood by a "spillway" or gigantic sluice, which was built at one end of the dam. During the constructional work all the water discharged by the Chagres and its tributaries flowed through the spillway. It is 300 feet wide, and is provided with gates by which the level of the water can be regulated. Through these sluices the water can pour in flood time at the rate of 140,000 cubic feet a second. There is no fear of the canal "drying out". I have mentioned before the heavy rainfall common to those parts. The lake impounds the waters of a catch-water area of more than 1300 square miles, and the rainfall is sufficient to keep the lake filled for eight or nine months. For the remaining "dry" months there is sufficient water in hand to allow for more than forty daily passages through the locks—a greater number, in short, than the locks can possibly handle.

The lake crossed, our vessel enters the famous Culebra cut, and for the next 9 miles we shall be passing through the biggest ditch ever dug by man. This passage through the Cordilleras ridge is the canal-builders' crowning achievement. You will remember that the hills here rise to over 500 feet, and although the middle-line of the canal passes through a natural valley between them, excavations had actually to be made at that height in order to obtain the necessary width at the bottom of the canal—300 feet—and the proper slope, or "angle of repose", of the sides of the cutting. The longitudinal middle-line or axis of the canal had to be cut from levels varying between 312 feet above sea level to within 40 feet of sea level for a distance of 9 miles.

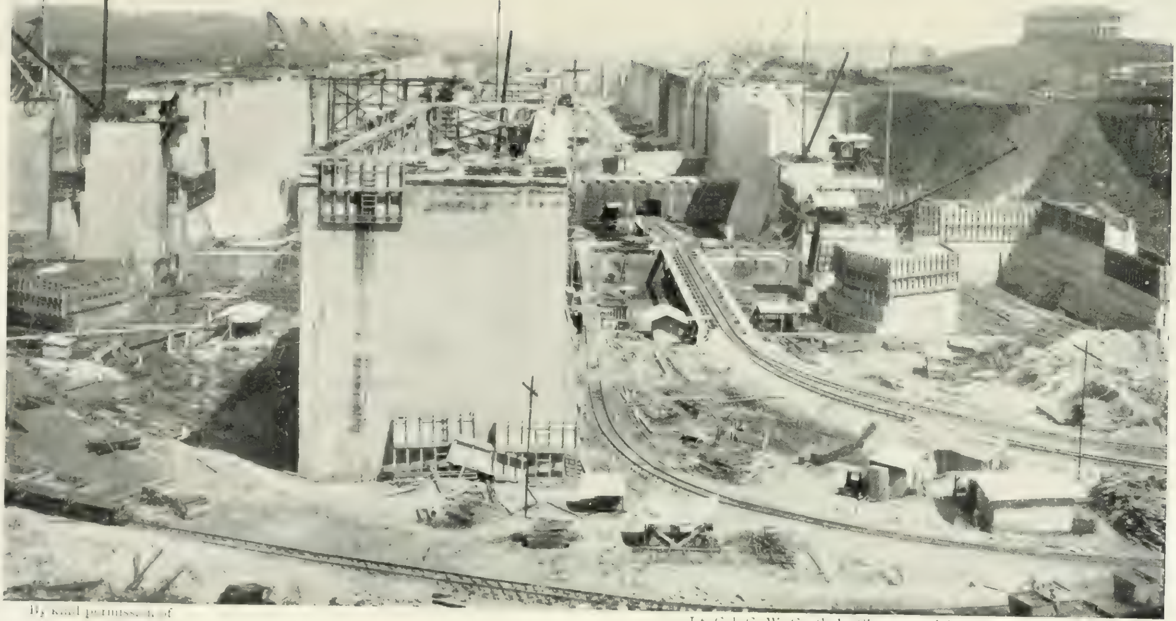
The excavation of the Culebra cut would have been an utterly hopeless task but for the wonderful machinery, and, still more, the wonderful organization that the American engineers brought to bear upon it. Fortunately the rock was fairly easy to work, being a soft variety of sandstone. The first process towards cutting it up and carrying it away was the making of the holes for the dynamite charges. Standing on the summit of Golden Hill, the 500-foot hill that forms one bank of the canal, between the years 1909 to 1912, could you have looked down upon the Culebra cut in the making, you would have seen an extraordinary spectacle. The hillside was scarred by terrace-like projections, making it look like a flight of gigantic steps. On each of the terraces there was, or had been, a railway track, and on each track were the mechanical drills and the great excavators. Each drill made a hole 30 feet deep in about eight hours. When sufficient holes were drilled, the machines were hauled out of the way, the dynamite "shots" were inserted, and the earth trembled under the shattering force of hundreds of explosions. Then came the excavators along the tracks, huge steam navvies, each of which could shovel up and load into the trains of waiting trucks 1200 cubic yards of broken rock a day—an amount equal to 600 two-horse loads. These steam navvies could bite out eight tons of "dirt" at a dip! It was stated in *The Times*, in 1910, that in the Culebra cut alone there were over seventy steam shovels, of from 45 to 90 tons, continuously at work, the "dirt trains" into which they were kept busy shovelling the rock requiring the services of no fewer than two hundred locomotives.

Having loosened the rock and loaded it into the trains, the next thing was to get the trains out of the way as quickly as possible, and then to get them back again ready to be re-loaded, so that the shovels should never be idle. Now, you know that the spoil could not be dumped just anywhere, but had to be carried to some place where it was needed, as, for example, the Gatun dam, or the breakwaters at the entrances to the canal. Arrived at their destination, the dirt trains were subjected to the tender mercies of an apparatus called the Lidgerwood unloader. The trucks were provided with flaps at the end, and when these were let down a continuous platform was formed all along the train; then, instead of the trucks tipping up, or opening their bottoms, to discharge their contents, the spoil was simply swept off them by a plough. This plough was drawn along the train by a wire on a drum on the last truck, and cleared the "dirt" off in next to no time. To be exact, the Lidgerwood unloader could clear a train of sixteen cars of its 320 cubic yards of rock and earth in seven minutes. But this was not quick enough for Uncle Sam. So he introduced larger dump cars, operated them by compressed air from the locomotive, and succeeded in emptying them of 600 tons of "dirt" in ten minutes!

It was so important that the spoil trains should work between the excavators and the dumping ground with the regularity of a shuttle that a special transportation department was organized, which exercised a very important authority on the work on the isthmus. Everything had to give way to the dirt train. What a gigantic business it was to get the excavated material out of the way may be judged from the fact that the total excavation reached the unthinkable figure of 212,504,000 cubic yards. The total excavation as originally estimated was 103,795,000 cubic yards. A cubic yard of spoil weighs, roughly, a ton.

An ingenious statistical fiend has been to the pains of working out for us just how that excavation would bulk if it were represented in pyramids. He tells us that it is equal to 8 miles of pyramids the size of the great pyramid of Cheops, set base to base; and that if it had been left loaded on the cars that brought it out, it would have made a train 96,000 miles long: certainly an awkward train to deal with, as it would be wound four times round the earth.

The excavation of the Culebra cut would have been a simpler business if the work had not been handicapped by the continual slipping that took place. The constant landslides gave the engineers a great deal of anxiety. These slides were glacier-like movements of soft material on slippery clay, and they occurred not only while the cut was being excavated but for a long time after the canal was otherwise completed. The canal was opened for traffic in the first year of the Great War, and was closed again on account of the landslides in the Culebra cut in the autumn of 1915, being re-opened again in the spring



By kind permission of Lt.-Col. G. W. Goethals, Chairman of the Isthmian Canal Commission.

THE PANAMA CANAL

The upper locks at Gatun in course of construction. View looking north.

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of 1916. At times there have been more than a million cubic yards of soil in motion, and though most of the slides are small, some have covered very large areas and have moved as rapidly as 14 feet in twenty-four hours.

To continue our voyage through the canal: at the end of the Culebra cut our ship is admitted to a lock which lowers us 30 feet to a small lake 54 feet above sea level. This lake is only a mile and a half wide, and having crossed it we are at Miraflores, ready to be locked out to the Pacific. Here is the counterpart of the dam at Gatun, but on a much smaller scale. There are two locks to pass through; and even then, though our keel is once again in salt water, we are not out of the canal, for we have to steam through a dredged channel for eight and a half miles before we are in deep water.

Our journey has taken us nearly twelve hours. We have traversed the most wonderful waterway in the world, for our eyes have seen the most distant places of the world brought nearer. And it does not signify much to be told that the notch the Americans have cut for us cost them four hundred and sixty million dollars. Whatever it had cost, the cost would have been justified.

CHAPTER X

The Safety of the Mariner

As sons of the greatest maritime nation the world has ever seen, the mariner's safety has a special interest for us. When Nature made our islands she gave them one of the greatest gifts she could bestow, carving our coasts into fine, wide, sheltered bays, and forming our river estuaries so that they should afford protection for the ships that were eventually to seek their shelter. In doing this, Nature took good care that the rise of the nation that was destined to people these islands, and to make them so famous, should not be too easy; for she put rocky prominences and sandy shoals just where the coming sea-kings would find them most inconvenient, and (one might think) she told her friend old Neptune to keep his eyes open and, if this coming people grew too cocksure of its own power and wisdom, to raise a storm now and again, just to keep it within bounds.

We are apt to think that Nature was unkind when she made such provision for our future, but really she was a wise mother. You know how lazy and stupid your dog becomes if, in mistaken kindness, you coddle him; and, more to the point, how fervently you despise the pampered boy, do you not? With dogs, or boys, or men, or nations, it is just the same; laziness and want of grit, stupidity and self-conceit are soon begotten when life becomes too easy, and they have things too much as they like them. You know what Kipling says—or you ought to, for he said it as a hint for boys—in the song about the camel's hump: how "the hump we get is uglier yet, from having too little to do"; Nature said the same thing, or meant it, ages and ages ago, when she carved our island kingdom; and she keeps on saying it when she hurls stricken ships on to the deadly Goodwins, or sends down first a blinding fog, and then drives them blundering to the rocks, where they thought no rocks to be. It is the Spartan method, which agrees alike with nations and with boys. We dislike it, just as we dislike many other things that are good for us; but that it is good for us every sensible boy and every wise man agrees in his heart of hearts. Without it, where would be the bravery and resourcefulness, the Anglo-Saxon firmness of purpose and power of endurance that are our great pride and the envy of other nations? Without the lurking rocks and cunning sands, without the smiling, growling, laughing, roaring old sea, which has given us our prosperity and our glory, and yet takes his awful toll of us, where would be the need for our Smeatons, our Rennies, and our Stevensons, and their lighthouses, their breakwaters, and their harbours of refuge?—in a word, what need would there be for guarding the safety of the mariner?

No nation is great until it has great works to accomplish; and the greatest works of the great nations of the world have had to do with hydraulic engineering. You know how the people of the Netherlands have had, literally, to wrest their country from the grasp of the sea, and how famous are their defences against their watery enemy. We have had the same enemy to contend with, though he has attacked us in a different manner; and the breakwaters and harbours around our coasts are numbered among the greatest of the engineering triumphs of the world. Let us start with the breakwaters.

The engineer whose business it is to protect harbours and roadsteads, by building breakwaters able to resist the fury of the gales, has to know a great many things to which other people never give any thought. If you have ever seen a storm during your holidays at Dover, or Eastbourne, or Aberystwyth, or a hundred other places, and have joined in the fun of dodging the waves as they dashed up against the sea wall, you may have some glimmering of what a really rough sea is like; but if on these occasions you have seen the waters hurling gravel on to the promenades, tearing down lamp-posts and throwing seats about, and perhaps making great breaches in the sea walls, then probably you are willing to agree that the sea can be a very ugly customer indeed. Only those who have an intimate knowledge of it have more than a rough idea of how terrific are the sea's powers of destruction; and only those who take the trouble to search beneath the surface can realize the ingenuity with which the engineer combats these powers. In fact, it is little short of incredible that the work of human hands can ever stand against the wildest forces of wind and wave, and it is only due to the care with which sea-works are designed, built, and continually watched that it is ever possible to protect our docks and harbours. There is, of course, no sense in making breakwaters too strong, for that would add to their cost; but it is equally clear that they must be strong enough to withstand the roughest seas and the fiercest gales.

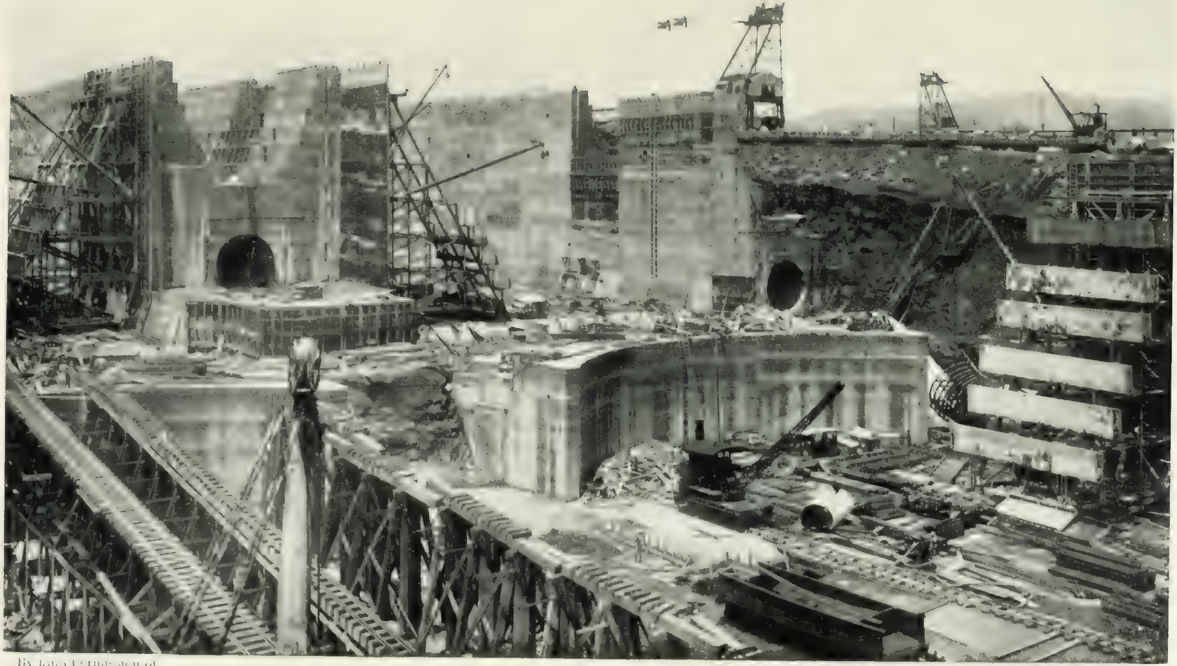
This question of strength is one of the first and one of the most important questions that the engineer has to consider. Before he does anything else, he arms himself with a great mass of data relating to the behaviour of the sea in the locality in which a breakwater is to be built. He studies the tides and the force of the waves and wind. The sea bottom has to be thoroughly probed, to discover its nature; and there are a hundred other things that must be considered.

It is not always the largest waves that are the most destructive, for the largest ones may be broken up by rocks or shoal water before they reach the breakwater, while smaller ones may exert an impulsive or smashing force by breaking directly on to the works. The study of the waves and their habits forms a very complicated but also a very interesting one, which it may be worth your while to take up one day, whether or not you have anything to do with breakwaters and harbours beyond an intelligent interest in these most useful works. It is impossible to enter upon it here, but it may interest you to know that in winter time some of the Atlantic waves that batter our coast are 40 feet in height, and exert a force on whatever they happen to strike equal to 3½ tons to the square foot. Small wonder that a little roller will sometimes bowl us over when we are bathing; and small wonder too that our western coast line is so rugged and indented! Many astonishing feats of strength—unfortunately exerted for destruction—have been recorded of the sea, and still are recorded from year to year. One of the most famous was accomplished many years ago at Wick, in Caithness. During a midwinter storm the waves tore from the breakwater a vast mass of masonry embedded in concrete, and bound together with iron bars 4½ inches in diameter. It was computed that this mass weighed over 1350 tons. Not content with merely tearing it from its seat in the breakwater, the gigantic seas picked it up and tossed it some distance away, as a mad bull might toss a child. After reading this we may well have an increased respect for the men who design and build breakwaters, and one not less, perhaps, for the force they would try to tame.

There are so many notable breakwaters in the British Isles that it is by no means an easy matter to choose from them one or two for special description here. But as a choice must be made, we cannot do better, perhaps, than start with one of the early ones, and work forward to those of to-day. Let us then start with Plymouth Breakwater—one of the most famous and most difficult engineering works of the last century—and see how it was made and what it is like.

If you have ever been to Plymouth, and have ever thought of it as it would be without the great breakwater, you cannot have failed to realize how utterly at the mercy of the storms the harbour would then be, especially to the south; and that was exactly the state of things that existed a hundred years ago, before it was determined to protect the exposed southern end. The breakwater, which is nearly a mile long, was commenced in 1812, and consists of three portions. There are two wings, which slope slightly towards the shore, their ends being separated from it by deep-water channels about half a mile wide. These wings are each over 1000 feet long, and connect with the middle portion of the breakwater, which has a length of 3000 feet. The water in which the breakwater is built is from 20 to 40 feet deep at low tide, and the waves gave the work a terrible buffeting during its construction. The method of building it was to deposit under water a vast mound of heavy blocks of sandstone. The rock came from a quarry near by, and was loaded into hopper barges—that is, barges having trap doors in their bottoms, through which the material was dropped into the sea. At one time it was thought that the breakwater could never be made, owing to the rough treatment to which the indignant waves subjected it. As soon as the structure, or part of it, rose above the surface of the water, a marked calmness was noticed in the condition of the waves inside it; but, as I have said, that desirable state of affairs did not last very long, for as soon as ever there was anything for the waves to pull down—that is, whenever the breakwater grew large enough for them to crash upon—the shape of the breakwater was altered and its slope flattened, and more boulders of rock had to be thrown upon it. This war between the sea and the engineers—a kind of "guerrilla" warfare, in which neither force gained any distinct advantage—went on for twelve years. In 1824, however, the sea gained a notable victory, for during a terrific storm it managed to dislodge a great portion of the breakwater, and to hurl it into Plymouth Sound. After that it seemed to weary of the game, and submitted to the building of its enemy with a better grace. In 1841, after more than *three million tons* of rock had been tipped into the sea, it was announced that the work was completed.

In this breakwater the stones simply lay one upon another, without any cement to bind them together, and to add to their security the sides of the breakwater were made very sloping. At the base it is 400 feet wide, and at the top only 45 feet wide.



By kind permission of Lt.-Col. G. W. Goethals, Chairman of the Isthmian Canal Commission

THE PANAMA CANAL

Work in progress on the middle locks at Gatun, looking south from lower locks.

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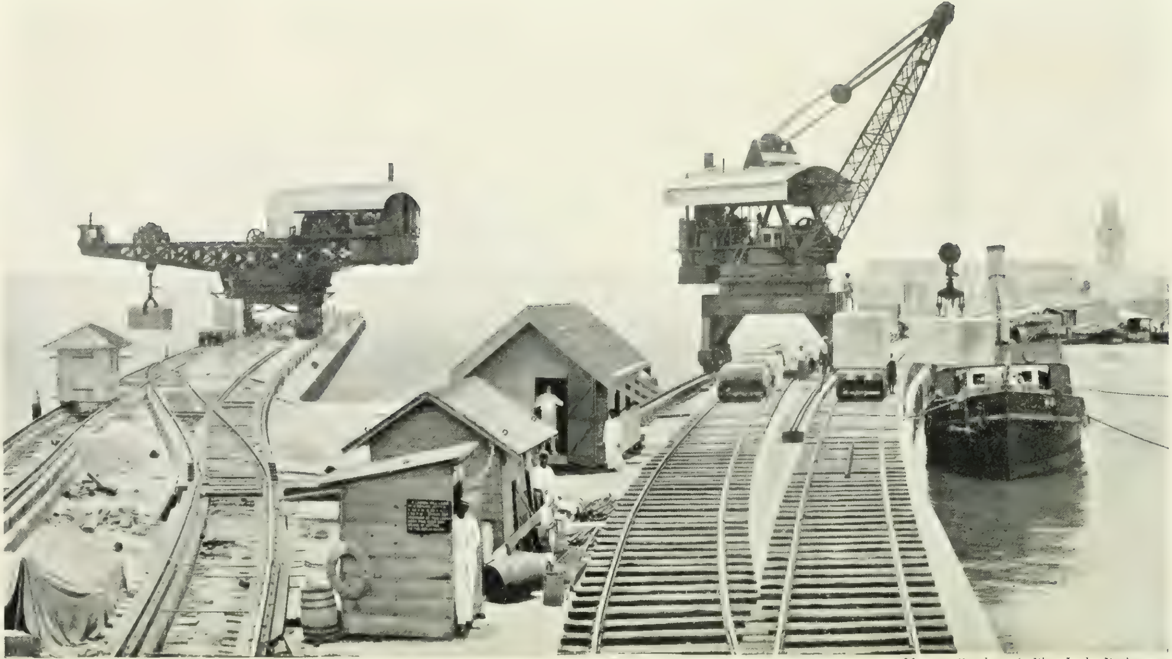


By kind permission of Messrs. Stothert & Pitt, Ltd., Bath

MACHINES FOR BUILDING BREAKWATERS

On the left hand is seen a block-setting titan, and on the right a "Goliath" crane. Note the great size of the concrete blocks.

The whole work was faced with masonry, and the total cost was nearly a million and a half. In later years Plymouth Sound has been further protected by the construction of a breakwater extending westwards from Cattewater harbour.

Devon begins with a D, and so does Dorset; Plymouth begins with a P, and so does Portland. Plymouth is the principal port of its county, and Portland is the principal port of *its* county; both are great naval stations, and both have their harbours protected by great breakwaters—and there the similarity ends. Portland has, indeed, one of the largest and safest harbours in the world, which owes its existence entirely to its magnificent breakwater; before this was built the expanse of water between the Dorsetshire coast and the island, or, rather, the peninsula of Portland was a storm-swept and unsafe anchorage. The breakwater is more than two miles long, including recent additions, and there are three openings for the passage of ships between the island and the shore. The work was commenced in 1847, the foundation stone being laid by Prince Albert two years later; and it was completed in 1872, the breakwater having taken twenty-five years to build. Its construction differs considerably from that of the breakwater at Plymouth, inasmuch as there is a masonry superstructure, founded on a great mound of rubble, or loose stones, rising from the bottom of the sea to low-water level, a height of about 50 feet.

Apart from its importance as an engineering undertaking, Portland Breakwater is interesting because it is built of stone from the famous Portland quarries, and is of material practically similar to that of which St. Paul's Cathedral and many of our great public and national buildings are made. It was built almost entirely by convicts from the great prison at Portland, and although nothing was charged for this labour the work cost the nation more than £1,000,000.

If you have read the chapter in which the story of the making of the Suez Canal is told, you will recollect that de Lesseps, the great French canal engineer, had to build a big breakwater to protect the Port Said entrance to the canal; and that, having no stone that he could use for this purpose, he fell back on the making of artificial stone. Of course, there is nothing uncommon about that nowadays, and it is not at all unlikely that you have walked on artificial stone many and many a time, without knowing it, perhaps, for the paving stones used in streets are often artificial, and are made in moulds, from different kinds of cement. Artificial stone, or, as we more commonly call it, concrete, has played a very important part in the making of many big breakwaters since the one at Port Said was built; and it will, therefore, be worth our while to take a closer look at this material, especially as, in doing so, we can have a peep at the same time at Dover Harbour and its great breakwaters.

While the breakwater at Portland was being built the Government turned its attention to Dover, with a view to discovering its possibilities as a great harbour of refuge. Dover has always been the key of England; but there was no lock until Nature took away the isthmus that joined it with Europe, and placed the Strait of Dover in its stead—for Dover was, probably, the last place at which England and the Continent were connected. Julius Cæsar made his first attempt upon rude Britain at Dover. The Romans made it a great city, with walls and gates, at the end of their Watling Street. Edward the Confessor strengthened it, William the Conqueror burned it, and during the centuries that followed the French besieged it time after time. Its fortifications were strengthened twice in the eighteenth century, and when Bonaparte threatened to invade England it was made "impregnable". It is still the key of England, and its white cliffs bristle with great guns, which are so carefully hidden that no one is supposed to know where they are placed. But it is only during our own era that Dover has become a great naval base. With the improvements in modern heavy guns, it would be helpless in an attack of to-day, unless it possessed a striking force capable of rapid movement. Without a fleet in the Strait of Dover, the town itself would be rendered powerless by an attack from the sea almost before it could fire one of its mysterious guns in reply. A few well-directed shells from a battleship lying far off would shatter its chalk cliffs, and bring down castle and guns and hidden forts together; and without its breakwater its fleet—the striking force—would be of little use to it. Dover Harbour protects from storm the fleet that protects England from attack.

Besides being the base of a great fleet of warships, the harbour affords a haven of refuge to the peaceful ships of commerce, and those who have aught to do with the Channel agree that it is a very necessary haven.

The work of building the breakwater was commenced somewhere in the forties of last century, as the outcome of the report of a parliamentary commission, which recommended that a sum of £2,500,000 should be spent out of the national funds for the purpose of converting Dover into a great harbour of refuge. The work was infinitely more difficult to carry out than that at either Plymouth or Portland, and involved an enormous outlay, owing to the fact that there was no suitable stone within easy distance. The water is very deep—42 feet at low water—and before the masonry could be put down vast quantities of shingle had to be removed. The breakwater was constructed of ashlar, founded on the chalk bottom beneath the shingle. Ashlar is a very substantial and costly form of masonry, and is composed of blocks of stone that have been dressed to a regular, square shape and set in mortar. The rubble of which the Plymouth and Portland breakwaters were made consists of rough stones, which are used just as they are obtained from the quarry.

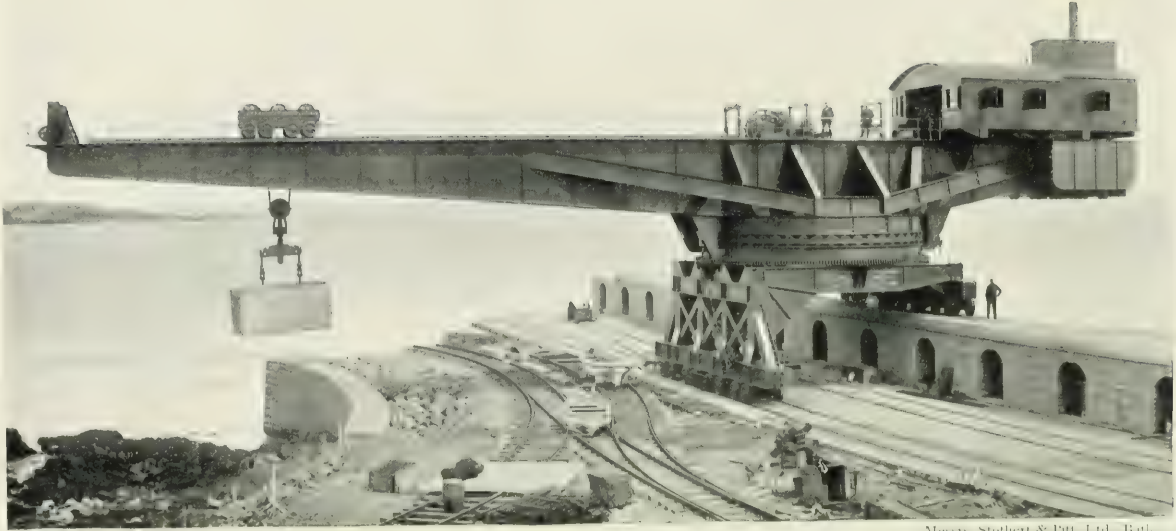
The breakwater at Dover, or, as it is more commonly called, the Admiralty Pier, is 4080 feet long and 60 feet wide, 1740 feet having been added to it since 1891. The courses of ashlar were laid under water by men working in diving bells. The diving bell is said to have been invented by John Smeaton, but this is a common mistake, for the origin of the apparatus is very much earlier than the eighteenth century. Indeed, there is good reason to believe that a primitive kind of diving bell—the *cacabus aquaticus*, or aquatic kettle—was used in Spain in 1538; and a timber structure answering the purpose of the bell was invented by Doctor Halley in 1720. The diving bell--which is now seldom used, its place having been taken by the pneumatic caisson, about which you read in Chapter II—is bell-like in shape, and is made of cast iron. The bottom or mouth is open, and inside the bell there is a platform on which the workmen stand. The apparatus is lowered into the water, and hauled out again, by chains connected with a crane on the pier or in a boat, as the case may be, and there is a pipe leading from the top of the chamber to a pumping engine above water. There is a valve in this pipe, to prevent the compressed air from rushing out again. Of course the water is kept out by the pressure of the air inside the bell, and the surplus air escapes past the bottom and rises to the surface of the water. The pneumatic caisson is an enormous improvement on the diving bell. It can be used at greater depths; it can be built to almost any size, though of course it cannot be moved so easily as the bell; the compressed air can be more nicely regulated in it, and the effects of the air on the health of the workmen are less harmful in its case.

To return to the Admiralty Pier at Dover, when a firm foundation had been reached, and a few courses of ashlar laid, the breakwater was built up box fashion, the middle being left hollow. Into this space concrete was poured, thus forming in the pier a solid core, protected by massive walls of masonry. After many years of hard work the pier was completed. That was a longer time ago than most of our fathers care to look back to, and since then there has been a very wonderful change in the appearance of Dover harbour, for new breakwaters, forming a semicircle outside the bay, have been built, and the work is scarcely finished yet. These breakwaters are rather peculiar, inasmuch as, instead of having very flat or sloping sides, they are made almost vertical. They are built entirely of huge concrete blocks, the blocks being made on shore and laid in position one upon another by Titan cranes.

In the making of these blocks, which may weigh anything between 30 and 50 tons each, according to their size, some interesting machinery is employed. Concrete is now so well understood, and so carefully made, that it occupies as a material for constructing great engineering works a place undreamed of thirty years ago. It must not be supposed from this that it is a new material, for it is really very old—there is good reason for believing that the Romans used it; but it is only within quite recent years that its use has become general. Apart from breakwaters, dock walls, and other marine works, it is used for a great variety of purposes where a little while ago engineers would have preferred to work with steel, or stone, or even timber. Railway bridges are built of it (when it is "re-enforced" with steel), and so are factories, warehouses, water towers, and a vast number of other things, right down to railway sleepers and telegraph poles. This useful and common material is composed of Portland cement mixed with certain proportions of sand and "aggregate", by which is meant any kind of stone broken up into small lumps. The cement itself is made of a mixture of lime or chalk and clay. These materials are first dried, then ground and mixed together, after which they are burnt in a kiln. Situated on the Kentish banks of the lower reaches of the Thames and on the Medway there are very many cement works, their great chimneys belching forth volumes of yellow smoke day and night. The factories have gathered in these situations because of the nearness of chalk and clay, the one abounding in the hills overlooking the rivers, and the other in the mud of the rivers themselves.

Wherever a work is being carried out involving the use of great quantities of concrete there is sure to be some interesting machinery for preparing it. If you should ever visit such a work, you will be better equipped for following what takes place if I give here a rough sketch of the processes.

If the aggregate to be used is rock, it will need to be crushed. As the rock is brought in from the quarry it is fed on to an endless band, which carries it to the crushing machine without further handling. It enters the hopper of the crusher, and passes between conical steel jaws, which crush it into small lumps as easily as coffee is ground in a coffee mill, to which machine the jaws bear in principle some resemblance. From the outlet of the crusher the aggregate again falls on to a band, and this time is carried to the washing and screening plant. The screen may be either rotary in its action or what is called a "jigger". In the former case the material is fed on to a conical sieve turning inside a drum; from this sieve, which rejects and discharges all that will not pass through it, it falls on to a second; this in turn sorts it out and passes it on to a sieve with a still smaller mesh, which deals with the sand. Water is circulating through the drums all the while, so that the ballast and sand are thoroughly washed. The screened stones, ballast, and sand are discharged by the machine into separate trucks, or, more probably, on to other conveyer belts. The "jigger" has a horizontal motion instead of a rotary one, and the material is automatically shaken from one screen to another until it has been sorted out to the proper sizes. Having been crushed, screened, and washed.



By kind permission of Messrs. Stothert & Pitt, Ltd., Bath.

THE LARGEST TITAN CRANE IN THE WORLD

This enormous machine was built for the construction of Peterhead harbour. It can pick up, swing round, and deposit exactly where required concrete blocks weighing 50 tons or more. It is self-propelling, and is carried on 32 wheels running on two lines of rails.

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it becomes necessary to mix the ingredients of the concrete. Sometimes the mixing machine consists of a number of vertical cylinders without bottoms, from which the materials flow out on to turning platforms, whence they are scraped by great arms, so arranged that they can separate the right proportion of each material. The next process is the mixing of the concrete, and for this purpose it is fed into a cylindrical machine which has a number of blades or paddles revolving inside it. These blades thoroughly mix up the cement, sand, and aggregate continually being fed into the machine, from which the mixture flows, in a semi-liquid stream, into tipping wagons. In these wagons it is taken to another yard, in which are arranged rows and rows of wooden moulds the exact size of the finished concrete blocks. Between the rows of moulds railway tracks are laid, and running on these, astride of the rows, is a giant crane, with a jib having a wide radius. The concrete is poured into the moulds and allowed to set; the moulds are then taken to pieces, the crane picks up the blocks, arranges them in orderly stacks, and the ground space is thus left free for the moulds to be put together again ready for the concrete that is continually coming in.

One of the illustrations shows the largest travelling Titan crane ever constructed. This Titan was built by Messrs. Stothert & Pitt, Ltd., of Bath, who are famous for cranes of this type. It is a great all-round crane, commanding the whole area comprised within a circle 200 feet in diameter, with the exception of the space in the centre upon which the crane stands. Within this area the Titan can lift and deposit, exactly where required, blocks weighing 50 tons. To do this at a distance of 100 feet from the centre of the crane requires not only great strength and rigidity in the lifting and load-carrying parts, but at the same time perfect freedom of movement of the monster cantilevers on the roller path supported by the great gantry framing, and of the crab running on the tops of the girders. To secure this precision and freedom of movement of the loaded parts, and of all the machinery, it is necessary to give great strength to all the structure, and to avoid any but the smallest swerving, or even elastic bending. The crane is larger than many of the opening bridges which are looked upon as of great size; and such a crane, with the roller path mounted on a foundation sufficient to replace the iron gantry shown in the plate, would make the provision of such a bridge a very easy affair. The Titan was used in building the Admiralty harbour of refuge at Peterhead, the breakwater of which is formed of artificial blocks of concrete weighing upwards of 50 tons each. The stormy character of the sea at Peterhead, and the great depth of water, necessitated the adoption of an exceedingly massive and strong design of breakwater, requiring for its construction blocks of great size and a block-setting crane of dimensions and power considerably exceeding those of any previously constructed.

The working load of the Titan is 50 tons, but the proof load was 62½ tons. In other words, the Titan will pick up a test load of 62½ tons and swing it round the circumference of a circle 200 feet in diameter—this weight being equal to that of a goods locomotive and tender. The machine is capable of lifting and lowering the load, slewing or revolving round the centre through a complete circle, and racking the load in and out horizontally. The whole machine is also self-propelling. It is carried by thirty-two wheels running on two lines of railway, one placed on the level of the breakwater and the other on the parapet. This required a difference of height between the sides of the under carriage of about 11 feet.

The difficulties of carrying on marine works in situations exposed to rough weather have not diminished since the days when the Plymouth and Portland harbours were built. At all events, the rough weather has not diminished; and probably the workmen who are swung in an aerial cradle over a boiling sea to their work would not care to admit that there has been much improvement in the conditions under which they labour. To the gang of men sent in a barge to drill holes in the rock as a preliminary to laying foundations for a sea wall, a rough sea and a high wind come as the vilest things that they can imagine. The barge is flung up and down, and the rock drills are in contact with the ground for a moment, and the next are lifted violently away from it. It was with the idea of rendering things easier, not to say more comfortable, for the builder of marine works that the "walking man" was invented. The "walking man" is so called because it can move about from place to place by moving its feet and legs. It is a massive erection, over 30 feet high, and is built of steel girders. It consists essentially of two steel frames, the inner one being a few feet narrower and about 10 feet shorter than the outer. Each of these frames has four legs, the legs being provided with "feet" 3 feet square for use when walking on sand, and with spikes for rocky ground. The legs can be raised vertically off the ground for a height of about 20 feet. The manner in which this astonishing machine walks is roughly this. Assume that the inner frame is close up against one end of the outer, and that all the eight legs are on the ground. The four legs of the outer frame are now raised off the ground by electric motors transmitting their power to the legs through gearing. The frame itself is next moved along the inner frame, also by electrical power, until it has reached the other end of the latter. The next step is taken by the inner frame. The legs of the outer frame are lowered and those of the inner raised, and the latter is moved to the end of its travel within the limits of the outer frame. The whole machine has now moved forward 10 feet, and the same process is repeated until it has reached the desired position. The great height to which its legs can be lifted from the ground makes it possible for the "walking man" to step over obstructions that lie in its path; and the fact that the inner stage can be moved sideways as well as straight forward gives the machine power to move in any direction.

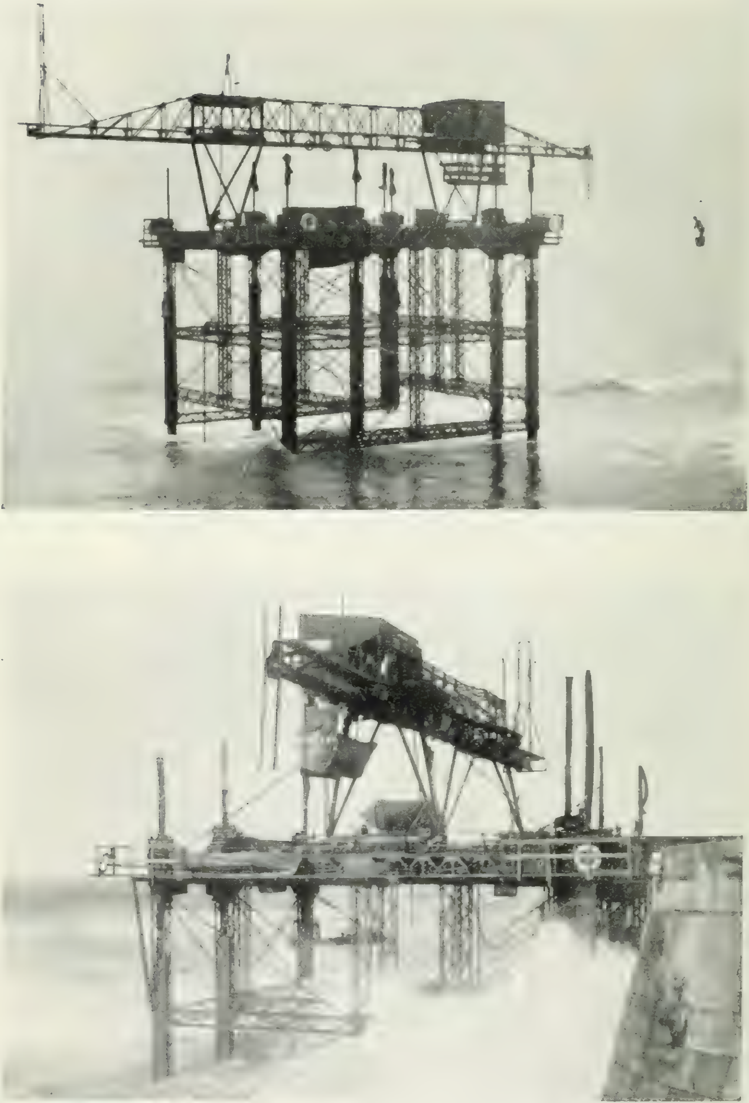
The "walking man" has been used in harbour work at Dover, at Whitby, and at Peterhead, on the exposed coast of Aberdeenshire, and so far has shown itself capable of maintaining its own in the roughest weather. This is due to the fact that its strong but slender construction offers little resistance to wind and waves. The machine is fitted with an overhead travelling crane for laying in their places blocks of stone or concrete, and carries machinery for rock drilling and blasting.

If we attempted to cover all the devices having for their object the safety of the mariner, we should find that, not a single chapter, but a whole book would be necessary, even if we did no more than touch upon them lightly. It is only possible, therefore, in this place to add to our list of the triumphant achievements of the engineer on the land and in the sea just a few words about those sublime works, his lighthouses. Landsmen are apt to forget these wonders of the engineer's art, with which they so seldom come into touch; but to the mariner "the coastwise lights of England" are of even greater importance than the breakwaters behind which he can seek shelter. We are all conscious of the romance of the lighthouse—of the spirit of humanity that finds expression as it flashes its warning, year in and year out, over 20 miles or more of reef-set sea; of the lonely life of those who tend it, brave men of many nations, guarding the welfare of their nation's commerce; of its strange and chequered history, with its stories of black villainy, of the luring of ships to hideous doom, of the work of the Cornish wreckers, the vilest scourge that ever sullied our maritime history; of the growth of the light itself, from the Pharos of the Roman navigators to the beacons tended by self-sacrificing monks beloved of fisher folk, and from the candles of Smeaton to the marvellous lamps of to-day. Of all these things we doubtless think as we stand on a summer beach listening to the purr of the gentle tide, and watching the widening beam of light sending its message over the star-lit sea; but if we were doomed to spend a wild winter's night in the tower of the Eddystone or the Longships or the Bishop's Rock, and could feel the structure shudder as the waves thundered upon its foundations, we should probably come away with a sterner idea of the dangers and difficulties that beset the lighthouse engineer.

Lighthouses have been built of timber, iron, and stone, although they are now invariably made of the last material, unless the waters in which they are situated are comparatively smooth. Before the present Bishop's Rock lighthouse, off the Scillies, was built, there existed an iron and timber lighthouse, which was scarcely completed before the sea picked it up and threw it away, snapping off the iron supports that had been fixed to the rock as though they were so much matchwood. After this experience the Brethren of Trinity House, who have the responsibility of looking after the lighthouses and lightships around the English and Welsh coasts, had a poorer opinion of iron construction for lighthouses exposed to the full fury of the gale, and built the new lighthouse of huge granite blocks.

The most famous lighthouse in the world is that which is built on the Eddystone rock, 9 miles off the Cornish coast and 14 miles south-west of Plymouth Breakwater. Doubtless you know the story of the Eddystone, but it will not be out of place if it is briefly retold here. In order to follow the story, we have to go back a matter of about 350 years, for, according to Mr. W. J. Hardy, who wrote a most interesting book on *Lighthouses: their Romance and History*, it was in 1665 that the suggestion for placing a light on "the Edie Stone", among other places on the south coast, was first put forward. But nothing was done until 1696, in which year Henry Winstanley commenced to build a lighthouse that he had himself designed. Winstanley was by profession an artist, and by nature something of a crank. In *Lighthouses: their Romance and History*, we are told that "besides being an artist, Winstanley distinguished himself in the science of mechanics, though the particular branch of that science in which he seems to have laboured was rather of the order to astonish than to yield profitable scientific result. His house and garden at Littlebury bristled with mechanical contrivances of every description. If you chanced to tread upon a particular board in the passage, forthwith a door at the end of it flew open, and out sprang a skeleton and stood before you; as you sat yourself comfortably on a seat in the summer-house, before which was a duckpond, the seat on which you sat was promptly swung round into the centre of the pond."

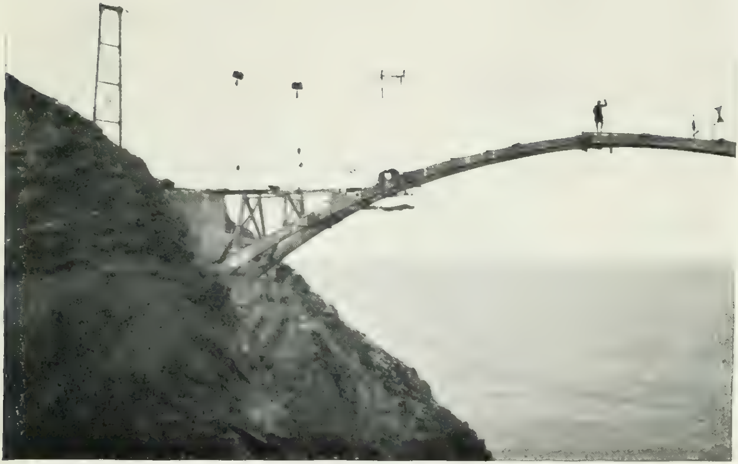
In 1700 Winstanley had completed his lighthouse, not without danger and adventure. The Eddystone rocks, you must remember, are 9 miles from land, and are submerged at full tide. The engineer and his handful of workmen suffered many privations on the lonely rock; they were nearly washed away by storms, and were once carried off by a French privateer. The lighthouse was an extraordinary structure, looking more like a debased Chinese pagoda than anything else. It was a polygonal tower 100 feet high, built of wood, and anchored to the rock by iron bars. It was ornamented with galleries, brackets, vanes, and flagstaffs, and a great deal of other top hamper—including two great symbolical candlesticks made of wood—equally fantastic and useless. Nevertheless, the lighthouse gave a useful light for three years; but its end was sudden and terrible, for in a terrific gale, which raged in November, 1703, it was blown completely away, together with its architect. However much we may smile at Winstanley's eccentricities, and at the quaint appearance of the first Eddystone lighthouse, we must



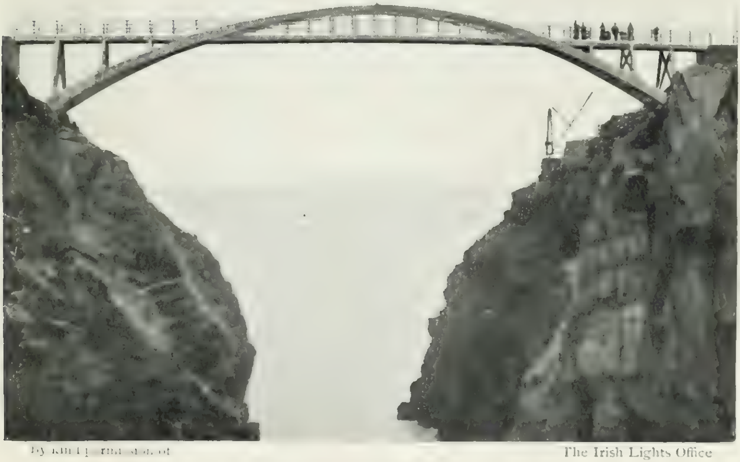
By kind permission of *The World's Work*

THE "WALKING MAN"

This is a wonderful machine recently invented for building harbour piers and breakwaters. It can move from place to place on its own legs. The lower photograph shows the machine at work in rough weather. *Page*



This view shows how the materials were brought up. The weather on the Irish Coast is so stormy that work on the bridge had to be stopped for a whole winter.



By kind permission of The Irish Lights Office

A DIFFICULT BRIDGE TO BUILD

In order to connect Mizen Head, on which is a fog signal station, with the mainland, a reinforced concrete bridge was thrown across the strait. *Fr*

not overlook the pluck and endurance and skill that he showed during the four perilous years he spent on the lonely Eddystone; nor must we forget that he did that which wiser and more famous engineers than he believed to be impossible—he built a lighthouse on a submerged reef 9 miles from land.

The second Eddystone lighthouse was commenced in 1706 by John Rudyerd, and was finished three years later. Rudyerd was a haberdasher of Ludgate Hill, and might not seem to be better qualified for building a lighthouse by virtue of his profession than was the artist; but, as a matter of fact, his erection was much more straightforward than ill-fated Winstanley's. His lighthouse also was built of wood, but it was strengthened by a core of granite, and for nearly fifty years it was a good friend to the ships passing through the Channel. How long it would have resisted the fury of the gale of its own accord there is no knowing, for it was burned down from some unexplained cause in 1755.

The third Eddystone lighthouse, thanks to its strength and the engineering skill it exhibited, was the most famous ever constructed, before or since, and was indeed worthy to rank with the great engineering feats of modern times. John Smeaton was the engineer who designed and built this wonderful work, which stood as firm in itself as the rock that supported it until 1881. Smeaton commenced his work in 1757, two years after Rudyerd's lighthouse was destroyed. It is said that he designed his structure so that it should have the shape and proportions of an oak tree. It was built of blocks of Portland stone, weighing from 1 to 2 tons, encased in an outer skin of granite. To ensure a firm foundation for the lighthouse, Smeaton dovetailed the blocks of granite into the solid rock. The base of the tower was 26½ feet in diameter, and the masonry was carried up solid for 13 feet from the base, the height of the tower being 85 feet. Smeaton's work has formed a pattern for practically all the lighthouses that have been built since his time, though, of course, there have been some alterations. His lighthouse is not now on the Eddystone rock, but stands on the magnificent Hoe at Plymouth. It was taken down, stone by stone, and put up again on the Hoe, when the rock on which it had been erected was found to be undermined by the action of the tide, and it was decided to replace it by a new one, built on a more stable rock. The new lighthouse was completed by Sir James Douglas in 1882. Except that it is larger and more solid than Smeaton's, the new lighthouse differs little from the famous one before it, but for one important particular. The present light—of 159,500 candle power—is, like many others round our coasts and abroad, supplied by an oil lamp, which burns a very high grade oil obtained from the Scottish shale beds; while Smeaton's light was obtained from 24 candles arranged on a chandelier—candles, moreover, that had to be snuffed every half-hour, to keep them bright.

Although you may never go to Plymouth, and thus may never see Smeaton's masterpiece, you do not need to look very far to find a picture of it. There were, and doubtless are still, millions of these pictures in everyday use—a national tribute to the genius of one of our great engineers—and you can buy them anywhere for a penny, a halfpenny, or a farthing; for the Eddystone lighthouse is represented on the reverse side of those coins issued up to about 1890, when the design was changed. Take an old penny out of your pocket, and there you have a realistic reproduction of the Eddystone rock, with Smeaton's lighthouse—a very small lighthouse, it is true—sharing with a very small ship in full sail what little room is left to them by a very big Britannia.

With the four examples just dealt with we must content ourselves, for there is no space here in which to tell of the building of other lighthouses, although there is scarcely one that, from the purpose it so usefully serves, or from the trouble that it took to build, is not worth our attention. The ease or difficulty with which lighthouses can be built depends of course on the situation of each, and on the approach to it. The tendency nowadays is to place lighthouses as near as possible to the water level, because from there both light and sound are more readily recognized by sailors than when they are high up. I say light and *sound*, because it must not be forgotten that nearly all lighthouses are equipped with foghorns, barbarous instruments of torture to landsmen who live near to them, but sweetest of sound-producers to the fog-bound mariner. On account of this tendency to lower the level of the lights, many lighthouses have been built on the rocks at the base of cliffs, where older ones existed on the summits of the cliffs. Beachy Head light is an example of this. The position in which the new lighthouse was built could not practically be reached except from above; and all the materials for building it, and, indeed, the workmen themselves, were taken to the site in cradles suspended from an aerial ropeway. The journey must have been anything but a pleasant one in boisterous weather!

A good example of the difficulties and dangers conquered by the engineer whose works warn seamen of dangerous reefs and promontories is the Mizen Head fog signal station, in the south-west corner of County Cork, a little to the south-east of Bantry Bay. Mizen Head is separated from the mainland by a narrow and rocky channel, and it was decided to connect them by means of a light bridge, so as to afford easier access to the signal station. As at Beachy Head, everything had to be carried across the channel by means of a ropeway; and it gives us a new and rather startling idea of the winter weather off the coast of Ireland to read that it was so severe that work had to be stopped, not merely for a day or two, *but for the whole winter of 1908–9*!

The Mizen Head bridge has a span of 156 feet between the abutments, and though it only carries a footpath 4½ feet wide, it presented some remarkable engineering features, on account of the difficulty of erecting it. It was partially completed in sections on shore, and then the different parts were placed in position by the help of the ropeway, and temporarily secured with wire ropes to the sides of the channel.

CHAPTER XI

Great Docks

In the last chapter we had something to say about our great harbours of refuge: let us now take a passing glimpse at those other works of the hydraulic engineer, the docks that have helped so much to build up Britain's commercial greatness.

A dock is generally an adjunct to a harbour, but it may be itself a harbour. It would not, for instance, be wrong to call Dover Harbour "Dover Docks", or, instead of speaking of Southampton Docks, to say "Southampton Harbour". A dock is an enclosure for the accommodation of shipping, and no one could grumble at us for applying the same description to a harbour; but a harbour, so called, is, as we have already seen, generally built to accommodate ships that are seeking refuge from stormy weather, while a dock, so called, is built to accommodate ships that are receiving or discharging their cargoes.

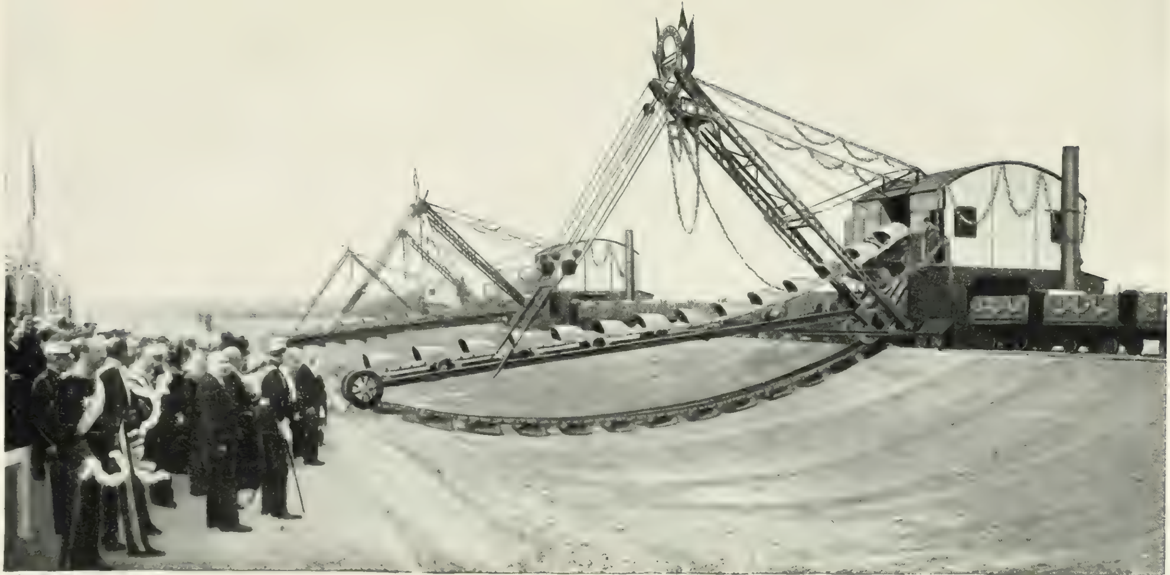
We might build a very fine harbour in which ships could ride safely in any weather, but it would be of little use for commercial purposes unless we provided a great many accessories and conveniences for loading and unloading the ships. Suppose we take

Teignmouth as an instance—merely because it serves the purpose of illustrating what I mean as ably as a hundred other harbours on the British coasts. The ships using Teignmouth Harbour enter it at high tide, and are warped (fastened with big ropes called warps) alongside the quay wall. When the tide goes out the ships are left high and dry upon the mud, and their decks are several feet below the quay wall. They look very picturesque; their masts and spars at odd angles, the sun shining on their coppered hulls, the bright town behind and the Devon hills and Devon sea on either hand make up a very pretty picture. But it is not appreciated by the shipowners, who think of the time their ships spend in harbour as time wasted; and we cannot blame them for disliking our pretty picture. To be landed high and dry on the harbour bottom does big ships no good, being apt to strain them: and undoubtedly it must be inconvenient to load or unload a ship whose deck is gradually getting lower and lower beneath the level of the quay, until it is 20 feet down or more; at least, it must mean a lot of running up and down hill for the poor stevedores. So Teignmouth and other little harbours of the same kind have to be content with the small ships that don't mind being rested on the mud, and rather enjoy taking two or three days to unload a cargo that ought to be unloaded in a few hours; while the bigger ships, with more dignity and less time, go to harbours where *docks* are provided for their comfort and convenience.

There are docks and docks, just as there are ships and ships. The simplest form of dock is that which has its mouth open to the fairway, and in which the water level rises and falls with the tide. So far as large and important ports are concerned, the tidal dock is useful only in situations where the range of tide—that is, the difference between the levels of high and low tides—is not great, as at Glasgow. The spaces for the docks are dredged to a depth sufficient to provide enough water to keep the ships afloat at low tide, and the dock sides are built of stone or concrete.

The most common form of dock is called a "wet" dock. Such docks are enclosures — sometimes of great space — protected on three sides by massive walls, on which are cranes and warehouses and railway lines; and on the fourth by gates similar to those that give entrance to the locks on canals. The vessel enters the dock gates at or near high water, and, the gates being closed, the water is held up inside the dock.

In recent years the problem of dock accommodation has become a very important and complicated one. It is cheaper to carry cargo in large vessels than in small ones, and the tendency nowadays is to construct very large ships. But just as the locomotive builder's designs are limited by the strength of the weakest bridge on the railway and the size of the smallest tunnel, so the shipbuilder's and shipowner's plans are hampered and restricted by the size



By kind permission of Messrs. Orenstein & Koppel—Arthur Koppel Amalgamated

LAND DREDGERS DIGGING A CANAL

This photograph shows the King of Spain (indicated by a star) at the inauguration of the Guadalquivir Canal. The great land dredgers can excavate [illegible] cubic metres a day.

Page [illegible]

of the docks in which their vessels will lie up, and the depth of water in the channels approaching the docks. London, the greatest port in the world as regards its tonnage and the number of the ships using it, has a dock accommodation that has not grown in proportion to the growth of its trade, to the great damage of its facilities for encouraging and retaining trade.

Not the least interesting part of a great dock is the machinery with which it is fitted. Apart from the great hydraulic pumps that supply power for pumping water into it, to make up for losses by leakage past the gates and evaporation, and from other causes; for opening and shutting the massive gates, and for "scouring" the dock of the mud and silt that find their way in with the tides, there is a great variety of interesting appliances for dealing with the goods that the ships bring in or take away with them. At those ports whence coal or ore is largely exported — Cardiff, Newport, and Swansea, on the Bristol Channel, and others on the East Coast —may be seen monstrous erections, called tips or hoists, which handle trucks of coal as easily as the grocer handles packets of tea or sugar. At the Penarth (Cardiff) docks of the Taff Vale Railway there are coal tips capable of dealing with over 400 tons of coal an hour, and at the Newport Docks even this huge capacity is surpassed.

The method on which these coal tips or hoists work is roughly this. The hoist is a great erection of steel girders, 70 feet high or more, having a platform that can be moved up or down by a hydraulic ram. Attached to the platform is a movable chute. The truck of coal, weighing perhaps 25 or 30 tons, runs on to a weighbridge to have its weight registered, whence it moves on to a turntable, which swings it round and tips it up so that it runs on to the movable platform of the hoist. Power is then admitted to the hydraulic ram that raises the platform and its load to the necessary height, perhaps 40 feet, perhaps 50 feet, or even 60 feet. The end door of the truck is released, the cradle in which it is carried is tilted up, and the coal "shoots the chute" into the hold of the steamer being loaded. Then the truck is swung back to a horizontal position, the platform descends, and finally the empty truck is shot off on to an inclined plane, and rolls away to join its brethren in the "empty" sidings, by which time the platform or cradle of the hoist is occupied by another full truck.

Coal is only one of many commodities that are dealt with in bulk at the docks. The mechanically-inclined among us might spend a very interesting week among the wonderful inventions and devices scattered in and about the wharves and warehouses on the dock side. We take so much for granted, and enquire so seldom into the romance of the common products that surround us, that few of us ever think of the mysterious hands that help to fill the coal scuttle or make the daily loaf; and to most of us a visit to a great dock brings a revelation of the wonders of applied science.

At most ports where grain is imported the grain is stored in bulk in big granaries or silos. It travels loose in the ship's hold, just like coal or iron ore, and is transferred from ship to land by means of a grain elevator. Generally the elevator consists of a bucket dredger, which is inserted in the ship's hold and lifts the grain on to a conveyor — an endless band that carries it in a perpetual stream to any part of the warehouse or silo. Or, instead of the conveyor being used, the grain may be drawn through pipes from the ship's hold by suction. Oil, again, is pumped through pipe lines direct from the oil-carrying ships to the underground tanks in which it is stored. But if we go any further into the means adopted by dock authorities for the rapid and cheap handling of merchandise, there will be no room left for speaking of docks as engineering works, and we must therefore leave this subject for another time.

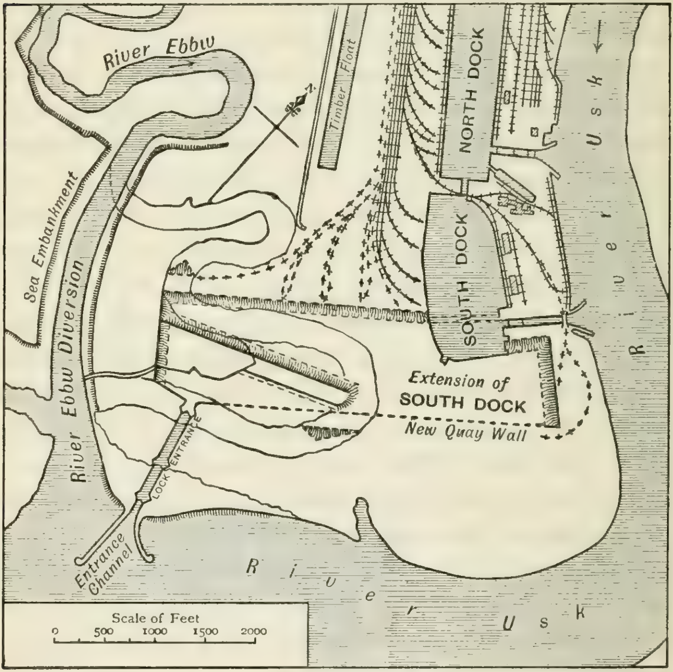
One of the British docks that have won for themselves a great reputation by their enterprise, and the rapid growth of trade that has come to them as a consequence, is that owned by the Alexandra (Newport and South Wales) Docks and Railway Company. The docks of this company are situated on the Bristol Channel, at Newport, in Monmouthshire, and provide the principal outlet for the produce of the Monmouthshire coal fields. Very important extension works were carried out at Newport not many years ago, which gave to the Monmouthshire port the right to boast of one of the very big engineering works, not only of Great Britain, but of the world.

It will be interesting to describe briefly what has been done at Newport, and in order that what follows may be quite clear, you had better take a good look at the sketch map showing the position of the old docks and the direction in which they have been extended (p. 278). The contract for the extension works was let by the Alexandra Company in 1905, the contractors being Messrs. Easton, Gibb & Son. The extension consists of a rectangular-shaped dock of 90 acres, with a depth of water of 33 feet, adjoining the existing South Dock, and running at right angles to it at its southern end.

Four large coal hoists, capable of discharging 600 tons per hour each, were built on the north slope, to deal with the increasing coal traffic. The other sides were originally sloped to a 3-to-1 angle with rubble pitching for a depth of 15 feet. Later in the contract it was decided to build a quay wall running the whole length of the south side, a distance of over 2200 feet, to deal with the export and import trade, which consists mainly of ore, steel rails, tin plates, railway material, &c. This wall is fitted with twelve hydraulic cranes, of 5 tons and 3 tons capacity. Behind it a large warehouse has been built, with extensive siding accommodation.

One of the most interesting features of the work was the diversion of the River Ebbw. The Ebbw, which flows into the Usk near its mouth, and is about 300 feet wide from bank to bank, ran through the site of the dock; and the first work of the contractors was to make a new channel for it. Operations were commenced by excavating the dry land, with the help of a Lubecker land dredger, for a depth of about 16 feet, the remainder being dredged after the banks at each end had been broken through and the water let in. The total quantity of excavated material was over half a million cubic yards. Heavy rubble stone dams, with clay backing, were built across the old channel, and considerable difficulty was met with in forming them, owing to the great rise and fall of tide—about 40 feet at spring tides. They were made by tipping the rubble out of trucks from a timber gantry, or jetty, which was built right across the river, and was available for working on after half tide. The water enclosed by the dock site between these dams was then pumped out. In the meantime, four steam navvies were excavating in the other part of the dock between the Ebbw River and the existing South Dock, sufficient bank being left to act as a dam between the dock on the one side and the river on the other. As soon as the Ebbw diversion had been completed and the water pumped out from the old channel, the steam navvies excavated this last bank, and completed the whole of the excavation on the dock site to the finished level.

In order to proceed with the foundations of the towers for the great coal tips on the north slope, the excavation at this point was pushed forward as quickly as possible and completed to dock bottom first. The excavation for the foundations of the first two tip towers was then proceeded with. These foundations were carried out in trenches in a manner to be described presently. They were founded on hard, cemented shingle about 16 feet below the level of the dock bottom, and were practically a solid mass of concrete built up to quay level. On this the steel-



work was built. Girders connect the towers with the quay, and carry railway tracks at quay level for the full trucks of coal. Steel trestles on concrete foundations carry the high-level roads for the empties, which are taken away by gravitation.

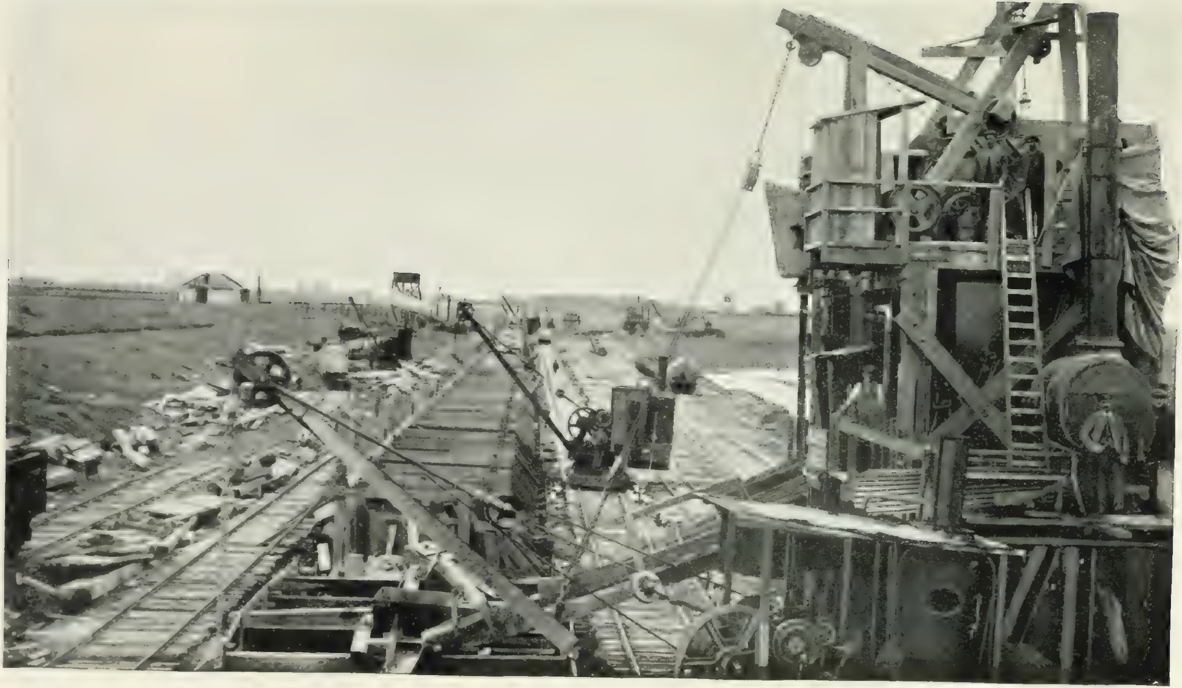
When the old Ebbw channel had been cleared, the remaining two tip towers were proceeded with. About this time the quay wall on the south side was ordered, and the work was proceeded with at once. The wall was built of concrete, with a slope in front of 12 to 1, the top 12 feet being faced with brindle bricks, with a granite cope. The width of the foundations was 20 feet, and the width at the top 10 feet 6 inches. The depth of the trench was about 40 feet. At the top of the wall a culvert was built throughout the whole length for the hydraulic pipes, electric cables, &c. Re-enforced concrete raking-struts, resting on a step at the back of the wall with a tie beam at the top, were built to take the outside rail for the hydraulic cranes. The total excavation in the trench for this wall was 65,000 cubic yards, and the wall was completed in ten months.

The water was let into the dock in September, 1907. The dam remaining between the new dock and the existing dock was then excavated by a bucket dredger and pumped ashore to raise the level of the ground round the dock in order to form railway embankments for sidings, &c. These sidings run for over a distance of 2½ miles to the north of tne dock.

At this time the existing lock entrance to the south dock was used for entering the new dock, but in January, 1907, a start had been made with the further dock extension and new lock entrance contract, which was also let to Messrs. Easton, Gibb & Son. This provided for an addition to the former dock contract, and for a new lock entrance with direct communication between the channel and the docks. When these were finished, ships were able to enter the new docks without having to go up the river Usk to the old entrance lock, while the further dock extension completes the rectangular shape of the former extension. The new lock entrance joins this at the south-west corner.

The new lock is of very great size, and large enough to take the largest ships that are likely to be built for a long while to come. It is 1000 feet long between the inside and outside gates, is divided by a middle pair of gates into two parts, of 400 feet and 600 feet lengths, and is 100 feet wide. The walls and invert are mainly of concrete, the walls being faced with blue brindle bricks. The depth of water over the outside sill is 45 feet at the high water of ordinary spring tides, and 12 feet at low water.

The quay wall at the south side of the former dock contract was extended in a straight line to meet the north-east corner of the lock entrance, a distance of about 1400 feet. The new docks, therefore, as completed, form a rectangular sheet of water, with a length of about 4000 feet and a width of 1000 feet,



BUILDING A GREAT DOCK

A general view of the excavations for the new South Dock of the Alexandra Newport and South Wales Docks and Railway Company. The machine on the right is mixing concrete, which is fed down the chute directly into the trench.

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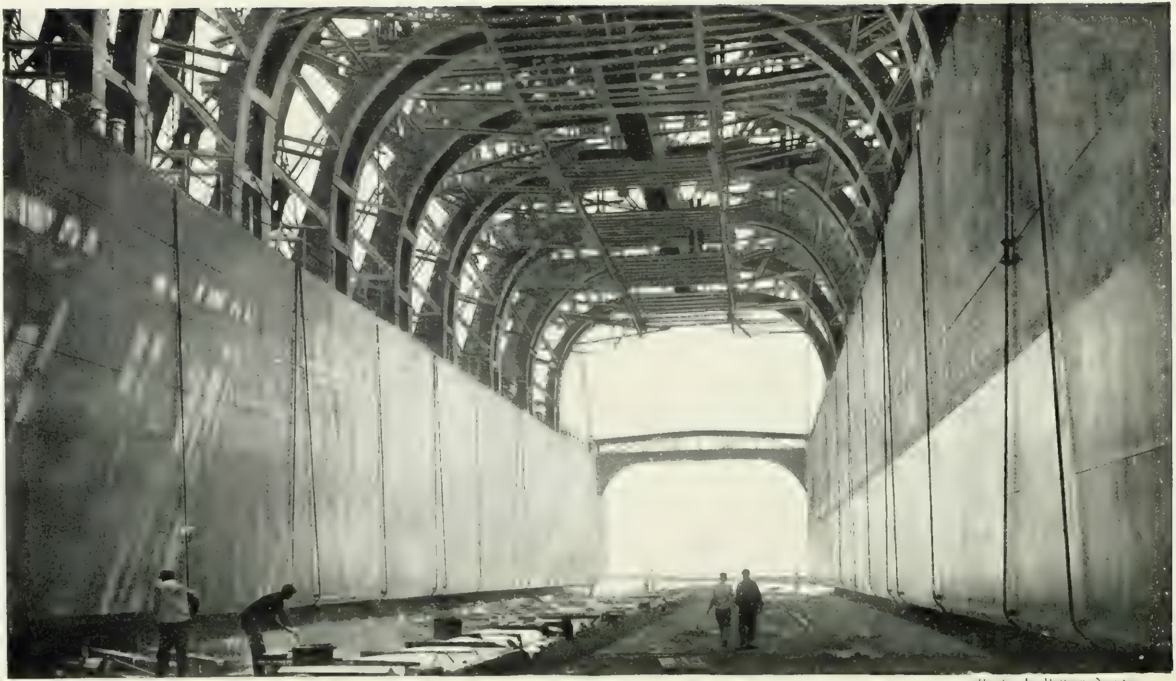


Photo. F. Pettier, Nantes

FOR RAISING SUNKEN SUBMARINES

A new kind of floating dock, built recently in France. By means of chains suspended from the girders a weight of a thousand tons can be raised from a great depth.

Page 280

having a lock entrance with sufficient water to admit ships at almost any state of the tide.

The method of excavating deep trenches, such as were used for building the walls of the dock and the foundations for the tip towers described above, is similar to that used in digging bridge foundations, and was described quite early in the book, when we dealt with the subject of cofferdams. In the case of the work at Newport docks, timber sheet piling, about a foot square, was first driven in around the site of the trench. The excavation was then proceeded with to a depth of 2 or 3 feet, and the sides of the trench were securely timbered by means of walings——large timbers placed in position against the sheet piling—and cross struts placed from one side to the other, butting against the walings. Of course the object of the walings and the cross struts is to prevent the collapse of the sides of the trench as the excavation proceeds, new frames of timber being added continually as the trench gets deeper. The material excavated is filled into skips, and lifted into wagons by cranes that travel alongside the trench; and as the wagons are filled they are taken away by locomotives to the tipping bank, which is formed to the required level for siding accommodation, railway embankments, or any other purpose that may be required.

When the trench has been excavated down to the level of the foundations, concrete is deposited to form the wall. As we saw in the last chapter, this is made up of crushed stone, sand, and cement in the required proportions, its manufacture being carried out in portable machines arranged immediately beside the trench. The mixture is tipped into a revolving drum, and water is added; and when sufficiently mixed the concrete is emptied out, and is led down by iron chutes to the trench. At Newport the contractors had their own quarry, about 12 miles away. There was a continual stream of stone sent down to the works by the railway, as many as six trains a day, of forty trucks, being used. Only about six hours elapsed between getting the stone from the quarry and its being placed as concrete to form the walls. Twenty locomotives were kept night and day dealing continually with the traffic for the work, and over 50 miles of railway were laid down. Twenty to thirty steam cranes were used for the work, and from 2000 to 3000 men were employed night and day. All this, together with the steam navvies, Lubecker land dredger, and bucket dredgers, presented a busy and fascinating spectacle, especially at night, when men and machines worked by the flare of electric and acetylene lamps.

The engineers had to deal with some big figures in carrying out this work. For instance, the main excavation amounted to four million cubic yards, independent of another million cubic yards of material removed by the dredgers, and over a quarter of a million cubic yards that had to be dug away to form the trenches. As the trenches were filled with concrete, it follows that over a quarter of a million cubic yards of that material had to be provided to take the place of the excavated "dirt"; and over half a million tons of stone rubble were used in forming the river banks.

The new naval base at Rosyth, on the Firth of Forth, was another harbour that embodied fine engineering work. Apart from the temporary work, such as the construction of an electric power station and engineering workshops, and the laying down of a great many miles of railway track, Messrs. Easton, Gibb & Son, the contractors, have had to carry out a great deal of work that may be called subsidiary to the docks proper. For instance, they have reclaimed an area of about sixty acres of land, which was previously under water; and, as if to compensate the sea for what has been taken away from it, they had to carry out extensive blasting operations, the island of Dhu Craig being blasted right down to water level. Indeed, the first operations required about twelve months' ceaseless activity on the part of a large army of workmen.

The much-discussed harbour scheme at Rosyth, which cost the nation such a large sum of money, included a basin for submarines, a dock capable of accommodating the largest warships, and a large graving dock. Great walls were built on three sides of a square, the fourth side being open to the waters of the Forth; and within this area the submarine dock was built. The walls extending seawards into the

Forth are 700 feet long and about 60 feet high, measuring from the foundations to the quay level. They are built of mass concrete, with a facing of Norwegian granite. There were huge stacks of the granite assembled at Rosyth, arranged so that they could be handled by the great cranes and traversers with the least possible delay. Each block was numbered with a figure, so that the workmen knew exactly into what part of the scheme it fitted.

The docks are protected by an outer sea wall of great dimensions. Owing to the swiftness of the current in the Firth of Forth the building of this wall presented considerable difficulty. It has been made of enormous concrete masses, formed of blocks, all of equal size and shape. Each of these masses weighs over 10,000 tons, and altogether a large number of them were used.

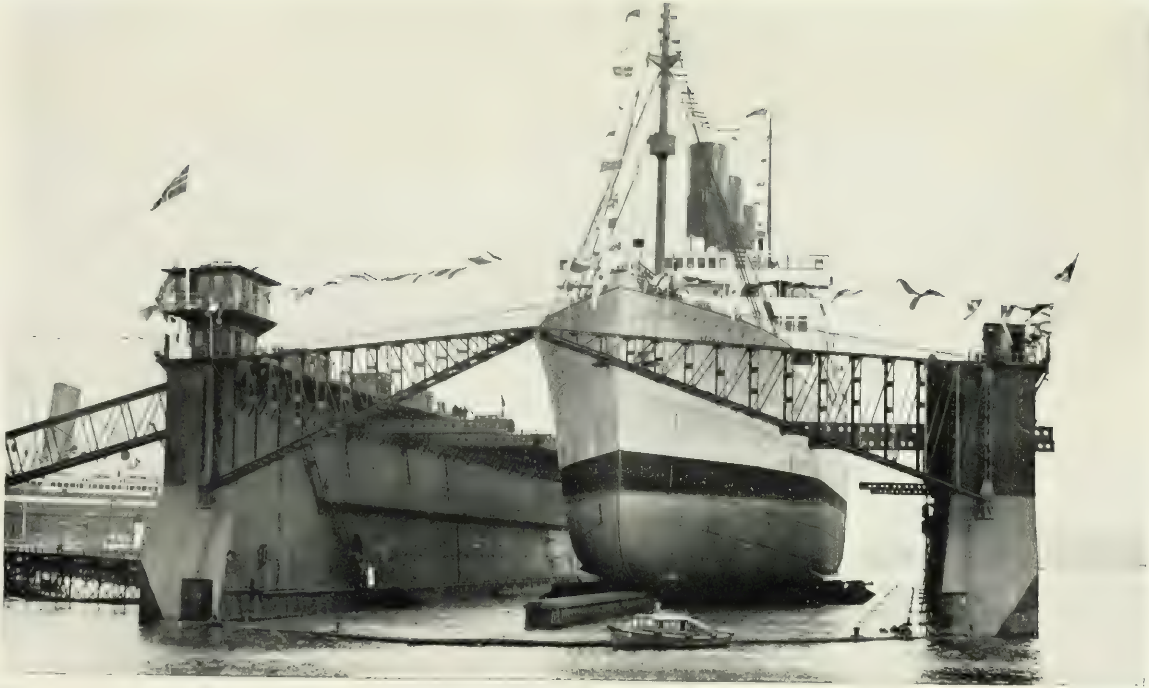
The sea wall is about a mile and a half away from the shore, and in order that the concrete could be put in position it was necessary to construct substantial timber jetties, or stagings, on each side of the site of the wall. The base of each concrete column is formed of a giant steel shoe, weighing upwards of 60 tons. These shoes were brought to the works in sections, and were there riveted up on pontoons, on which they were floated to their destined positions. If you read the account given earlier in this book of the sinking of the cylinders of the Hawkesbury River Bridge, you will remember that "grabs" were used for removing the soft material from the insides of the cylinders as they sank lower and lower. The same method was adopted in the case of the columns for the Rosyth sea wall. A space was left in the middle, between the blocks of concrete, and through this were drawn the mud and sand and gravel, giant steam grabs being used. When the columns reached a hard rock bottom the spaces between the blocks, and the interior of the shoe itself, were filled with concrete.

Mention was made just now of the graving dock at Rosyth. So far we have only touched upon wet docks, so called because the vessels in them are kept afloat. But it is often necessary for a ship to go into dry dock, to have her bottom examined, repaired, or painted. Graving is the act of scraping or painting a ship's bottom, and graving dock and dry dock are terms with one meaning. Inasmuch as it is a rectangular enclosure with masonry walls, the dry dock resembles the ordinary wet dock; its walls are not perpendicular, however, but slope upwards from the bottom, and are cut into flights of broad stone steps called "altars". The bottom of the dock is made of concrete, great longitudinal balks of timber, fastened down so that they shall not float, being laid on the concrete to prevent injury to ships' bottoms as they take the ground, and to enable the shipwrights to get right underneath the keels for examination. The docks are entered through a lock having a pair of folding gates, although big docks are occasionally closed by a caisson, an erection like a great sliding steel door which can be moved into a chamber built for it beside the dock.

Floating docks frequently take the place of the ordinary graving dock, especially in America. The floating dock is less costly to build, and takes much less time in the building—about one year, for instance, as against the two, three, or even four years required for building a solid graving dock. The floating dock has another advantage in its movability, and some very large floating docks have been constructed. It is possible to build a large floating dock at a steel-works in England and to ship it in pieces to a colonial naval station or coaling base, where the construction of a graving dock would be a very costly and difficult business. Or the floating dock may be put together and towed out to its destination complete and ready for use—an unwieldy and dangerous charge for the towing ships, as the loss on the high seas of a number of floating docks has amply shown.

The floating dock is built on the principle of an enormous caisson. Imagine two packing cases of the same length, one being wider and deeper than the other. Place the smaller inside the larger, and join them together with connecting pieces at the bottoms and the sides. There is thus formed a hollow space between the walls and the two bottoms; and if the ends were closed up so as to exclude the water from this space, we should have a ⊔-shaped pontoon of great buoyancy. A floating dock is built of steel plates riveted on to a frame-work of massive steel girders, the space between the inner and outer skins being divided by bulkheads into a series of watertight compartments. The dock is submerged by flooding these compartments, the ship to be drydocked is warped in position between its walls, the water is pumped out of the buoyancy compartments, and the dock, with the ship in it, gradually emerges from the sea until at last the ship is held up high and dry above the waves. A floating dock carries its own machinery—powerful steam engines and centrifugal pumps—for raising and lowering it; and on its sides there are stages and gantries fitted with cranes and other machinery for repairing disabled vessels. A floating dock recently built in England for the Brazilian Government can accommodate "Dreadnoughts" of the largest size.

We must not leave the subject of floating docks without making reference to the latest development of the science. We have all read from time to time of the terrible disasters that befall the latest engine of modern naval warfare, the submarine; and whenever we have news of the sinking of a submarine our hearts fill with pity, for experience has shown that there is little hope of raising the vessel in time to save her unfortunate crew. Within the last few years naval architects have devoted much time to the perfection of a craft which will be able to raise sunken submarines; and although they are still a long way from the ideal of perfection, there are now in existence several submarine docks. Germany was the first in the field with such a dock, and in the autumn of 1911 France launched her contribution. The German dock was more of the nature of a ship than the French, since it has its own propelling power, which the French has not. The latter is a very interesting construction. It is a great hollow-sided well, shaped at the bows like a ship. It is 328 feet long and 82 feet wide. It has no bottom, for there is a great space of 42 feet wide open to the sea. This space is arched across with ten girders, and the sides are also connected at the top with great lattice girders, to give the dock rigidity and strength. From the girders at the bottom of the dock mammoth chains are let down into the water, and when the dock is called to the assistance of a sunken submarine, divers will fasten these chains to rings provided on the submarine, which will then be hoisted into the dock and taken into harbour. The chains and the motors for winding them are able to lift a dead weight of a thousand tons from a great depth of water.



WORLD'S LARGEST FLOATING DOCK

The wonderful floating dock at Southampton is 1000 feet long and can hold the largest ships in the world. The pumps for emptying the compartments, as well as the cranes and traversers, are electrically worked.

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Conquests of engineering

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